Study Group 6

ELECTRONIC FUNDAMENTALS

Theory Lesson 11:	D-C Meter Theory
Experiment Lesson 11:	Calculation of Meter Multipliers and Shunts
Theory Lesson 12:	D-C and A-C Generators
Experiment Lesson 12:	Meter Assembly and A-C Measurements

RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA

New York, N. Y.

ELECTRONIC FUNDAMENTALS

THEORY LESSON 11

D-C METER THEORY

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11-2. Meter Scale

11-3. Commercial Meter Movements

11-4. Movement Used as Voltmeter

11-5. Current Ranges

11-6. Ohmmeter Circuits

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RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA

HOME STUDY SCHOOL

350 West 4th Street, New York 14, N. Y.

Theory Lesson 11

INTRODUCTION

Meters of one type or another are used in laboratories and radio and TV repair shops more often than any other kind of electrical test equipment. As a serviceman, you will use a meter more than any other kind of test equipment. You have already begun to use the d-c section of your multimeter to measure voltage, current, and resistance. As you use your meter to make other measurements, you will need to know something about how it works. The more you know about the circuit of your meter, the more intelligently you will use it. Also, you will want to know how to find trouble in the circuits and the movement of your meter if it becomes defective. In this lesson, you will learn about basic meter circuits and movements. (The circuits and movements of most meters are much the same as those that are used in your multimeter). Remember that repairs on the meter movement itself should be left in the hands of a skilled meter repairman.

11-1. PRINCIPLES OF METER MOVEMENTS

Motor Action. A brief explanation of motor action will help you understand how a meter movement works. In Fig. 11-1*a*, the cross section of a wire of nonmagnetic conducting metal, such as copper or aluminum, is shown in the field between the north and south poles of a permanent magnet. With no current through the wire, no motion is produced. However, if we pass a direct current through the wire, as shown in Fig. 11-1*b*, a magnetic field is produced around the wire. When the electrons in the wire come toward you, as shown, the lines of force have a clockwise direction. Let's see what happens when the conductor and its field are placed in the field produced by the two fixed magnetic poles, as shown in Fig. 11-1*c*. As you know from your study of electromagnetism, flux lines that point in the same direction repel each other and those that point in opposite directions attract each other. So, the movable conductor travels in the direction shown. Reversing the polarity of *either* of the two magnetic fields will reverse the direction of the mechanical force, but reversing the polarity of *both* fields will keep the force in the same direction.

The forces that cause the coil to move depend on three factors: the strength of the moving coil field, the strength of the permanent-magnet field, and the placement of the coil in the field. If the strength of either field is increased, the force acting on the moving coil is increased. The strength of the permanent-magnet field can be increased by using a stronger magnet. The strength of the moving coil field may be increased in three ways:

1. By increasing the amount of current flowing in the moving coil

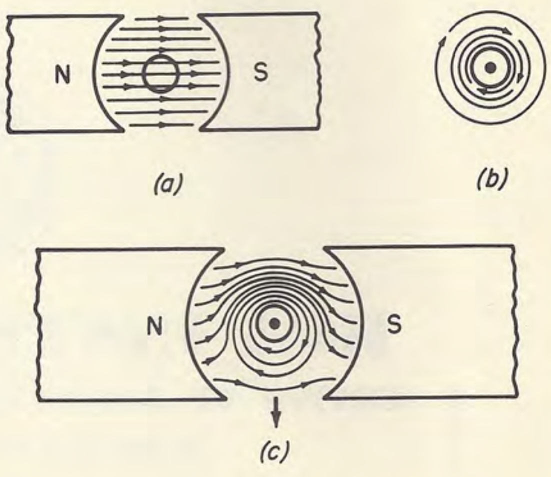


Fig. 11-1

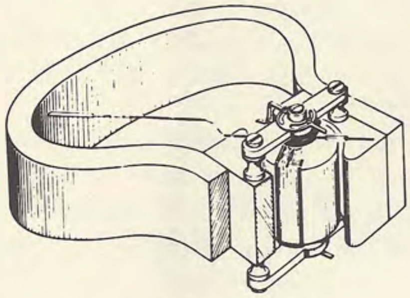


Fig. 11-2

2. By increasing the number of turns in the moving coil

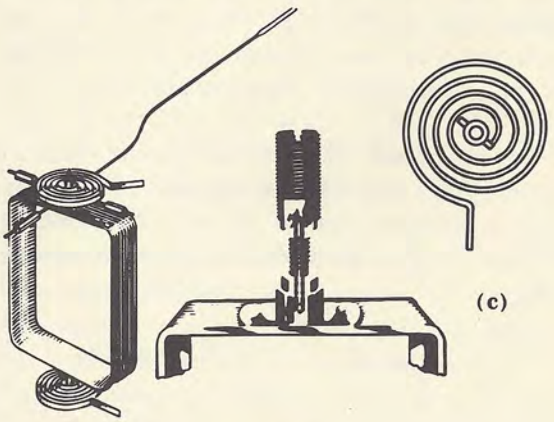
3. By using a core with less reluctance (greater permeability) in the moving coil

The force acting on the moving coil is greatest when the turns are at right angles (90 degrees) to the lines of force of the permanent magnet. This force becomes less as the angle is made less than 90 degrees. When the wire is exactly parallel to the lines of force of the permanent magnet, the force acting on the coil becomes zero.

D'Arsonval-Weston Meter Movement. While the moving-coil meter movement is very often called the D'Arsonval movement, it is better called the D'Arsonval-Weston movement. In 1856, an English experimenter named Vanley received a patent on the first moving-coil movement. This first meter was not very sensitive and would not be of much use in making many of the measurements servicemen must make each day. However, a French scientist named D' Arsonval, working along the same basic principles, produced a much more sensitive meter movement. The only trouble with his movement was that it was so delicate that it could be used safely only in laboratories. It remained for Dr. Edward Weston, another Englishman, to develop the first moving-coil movement that was both sensitive enough and rugged enough for wide practical use. Modern moving-coil meter movements are much the same as Weston's meter. They differ from his mainly in the improved quality of the materials and methods used in making them. The moving-coil meter uses the action of two magnetic fields on each other. This is called the motor principle. It is the same principle that is the basis of electric motors, relays, solenoids, and many other electromagnetic devices. Let's see exactly how this meter principle works in a D'Arsonval meter movement. A cutaway view of such a basic meter movement is shown in Fig. 11-2.

The horseshoe-shaped permanent magnet supplies the steady magnetic field to the gap in which the coil is supported. The soft iron pole pieces concentrate the magnetic field in the gap in which the coil moves. The pole pieces are shaped to keep the field intensity uniform in all parts of the gap, which is necessary if the scale of the instrument is to be linear. (A linear scale is one in which there is an equal distance between calibrations of the same units.) The soft-iron core of the coil is held in place by supports that do not interfere with the normal movement of the coil. The core completes the magnetic path between the pole pieces and makes the air gap in the magnetic circuit as short as possible.

The moving coil itself, shown in Fig. 11-3*a*, is wound of very fine insulated copper wire on a light *bobbin*, or frame, of thin aluminum. Two hard steel pivots, such as the one shown in Fig. 11-3*b*, are fastened to the bobbin, and their highly polished points rest in jewel bearings. The upper bearing is mounted in a bracket of nonmagnetic metal,



(a) (b) (c)

Fig. 11-3

which is fastened to the pole pieces. The other bearing is similarly mounted, but is hidden by the core. With this suspension, there is little friction for the coil to overcome as it rotates.

Meters with the pivot-and-jewel suspension can stand the normal jars and vibration met in everyday use and handling, but they should be treated with the same care you would give a fine watch.

The springs at either end of the coil are very important parts of the meter. One spring is shown separately in Fig. 11-3*c*. The current is conducted through the springs to the coil. The springs also supply the mechanical force for returning the coil to its original position after the current stops flowing. These springs operate like the door checks or door springs that you've seen on doors. When a door with such a spring is opened, the spring opposes the opening force. As soon as the force is removed, the spring acts to close the door. Not only does the spring close the door, but it also keeps the door from swinging open too far. The spiral springs in the meter movement have the same two effects on the moving coil; they keep the coil from swinging too far and they return the coil to its original position after a measurement has been made.

The meter pointer is attached to the coil. When the coil moves, the meter pointer moves with it. When the coil is in its original position (not moved) the metal pointer points to zero on the meter scale.

An important point about the springs is that they are spiralled in opposite directions. This is done so that if there is any change in their length or stiffness, due to age or changes of temperature, the changes will balance each other out and not change the zero-current position of the coil. The springs must also be good conductors and nonmagnetic so that the accuracy of the meter will not be affected. The springiness of the springs should remain the same with age and with normal changes in temperature. If the springs become weaker, they will allow the coil, and, therefore, the meter pointer, to reach a given scale reading with less current than if the springs were at full strength.

Friction in the movement is never desirable, but it is much more serious if the friction is not the same at all points in the travel of the moving parts or if it varies in different positions of the moving parts or at different temperatures. However, the design and mechanical perfection of the jewel bearings in even a moderately priced instrument are so good that usually the slight friction is not important. However, even the best of instruments may develop friction if abused; therefore it pays to be careful when you use your meter. In Service Practices 8, a method of testing for friction and other troubles in meter movements is given.

The *inertia* of the movement is very important too. Inertia is the opposition that a body offers to any change in motion. If a body is not moving, inertia tends to keep it from moving; if a body is moving, inertia tends to keep it from stopping. For example, an automobile needs a lot of power to overcome inertia when starting up from a position of rest. It needs plenty of braking power in order to stop it once it is in motion. The inertia of a meter movement depends upon the weight of the whole moving-coil assembly and the distribution of that weight around the turning axis. It is very desirable to keep the inertia of the movement as low as possible. The lower the inertia, the more quickly the coil will turn to the final reading, and the less it will tend to swing back and forth past the actual final reading before settling down. If the movement is at rest, the movement cannot move instantly to the reading, any more than a car, in starting, can leap instantly to full speed when you step on the gas. So the meter movement must be speeded up from zero speed to the speed at which it swings to the reading; this takes force, and time. Also, once the movement is swinging, force will be required to bring it to a stop at the end of the swing. The lower the weight of the moving-coil assembly, the less trouble there will be from inertia. In commercial meters of good design, the total weight of the moving system, including the pointer, is often a very small part of an ounce, even though the movement may be made up of as many as sixteen separate parts.

Damping. In good meters, the amount of overswing in coming to a reading is reduced by electrical or mechanical *damping*. Damping is the retarding or checking of the swinging motion of the coil. Without damping, the needle would tend to swing back and forth until it gradually came to rest at the proper point on the meter scale. In one system of electrical damping, a magnetic field is produced around the aluminum frame of the moving coil. This field is always in a direction that opposes the permanent magnet field, and it tends to oppose the movement of the coil. In practical instruments, damping usually lets the pointer reach its final rest position quickly, with very little overswing. This makes the meter more convenient to use and also reduces the likelihood of damage when the pointer is driven off scale by reversed polarity or moderate overcurrent.

Meter Accuracy. Most makers of moving-coil meters state the accuracy of the meter as a percentage of full-scale reading. For meters of moderate price, the accuracy will usually be about plus or minus two percent (±2%). For laboratory-standard purposes, careful hand adjustment and calibration can provide meters reliable to within one-half of one percent, or even one-tenth of one percent. Of course, the over-all accuracy of an instrument like a multimeter depends not only on the accuracy of the basic movement, but on the accuracy of other parts of the circuit as well.

Meter Sensitivity. When choosing a meter to buy and use, remember that the sensitivity of a meter has a great deal to do with its usefulness. An instrument that requires 10 to 20 milliamperes to give a full-scale reading is useless for measuring a current of one or two microamperes. However, the cost of meters usually goes up with the sensitivity. Thus, it would be a waste of money to use a meter that reads full-scale on 50 microamperes for measurements in which the lowest reading will never be less than several milliamperes.

Sensitivity is actually a way of saying how much current must flow through the coil to produce a swing of the indicating needle to full scale. Usually, sensitivity is spoken of in milliamperes or microamperes. A good meter movement for a volt-ohm-milliameter of the type commonly used in radio work will require 50 microamperes for a full-scale reading. This sensitivity is expressed in *ohms-per-volt* when the whole instrument is considered as a voltmeter. For example, the movement of your multimeter is rated at 50 microamperes, or 20,000 ohms-per-volt.

The sensitivity of a movement is determined by the magnetic flux in the gap in which the coil moves, the number of turns of wire in the coil, the resistance of the coil, the elasticity of the springs, and the friction in the pivots. If it were practical to double the number of turns in the coil without changing the resistance, only one-half as much current would be required to force the pointer to full scale. However, in order to double the number of turns without any change in resistance, it is necessary to use wire of double the cross-sectional area. A coil wound with such wire will weigh four times as much and will take considerably more space. The added weight will put more load on the bearings. Therefore, it will increase the friction and add to the inertia. A more practical way to get greater sensitivity is by increasing the strength of the magnet instead of adding turns to the coil. Today it is possible to have practical, portable multimeters that reach full-scale readings on as small a current as 10 microamperes. Used as a voltmeter, the same instruments have a sensitivity of 100,000 ohms-per-volt.

11-2. METER SCALE

The most desirable meter scale is one that is linear. A linear scale, you remember, is one in which the marks on the scale are equally spaced. For example, with a linear scale, each time the current is increased by

Fig. 11-4

5 ma, the neędle moves an equal distance from one calibration to the next. In order that the needle be deflected an equal amount for an equal amount of current, it is necessary that the magnetic field in which the coil moves be of uniform strength in all angles through which the coil moves from zero to full scale. A linear scale is shown in Fig. 11-4. Good meters usually have linear d-c scales that are accurate enough to make it possible to print scales for all meters of a given model on a printing press. However, the scales of laboratory instruments are often hand-calibrated for each individual instrument, giving a slightly better over-all accuracy.

The accuracy of the calibration of the original model of a given instrument affects the accuracy of each unit produced. Usually, several models of the meter to be produced are hand calibrated, and the calibrations are averaged in preparing the final scales to be printed. In this way, all movements will be within a certain tolerance, so far as scale errors are concerned. The thickness of scale markings affect the accuracy of the actual reading. Very thick markings are easy to see, but they increase the error in reading.

The scales of general-purpose instruments are made with reasonably heavy lines. The hand-calibrated scales of a precision laboratory instrument usually have considerably finer lines. The thickness of the needle pointer also affects the accuracy with which a meter can be read. Laboratory instruments usually have thin pointers.

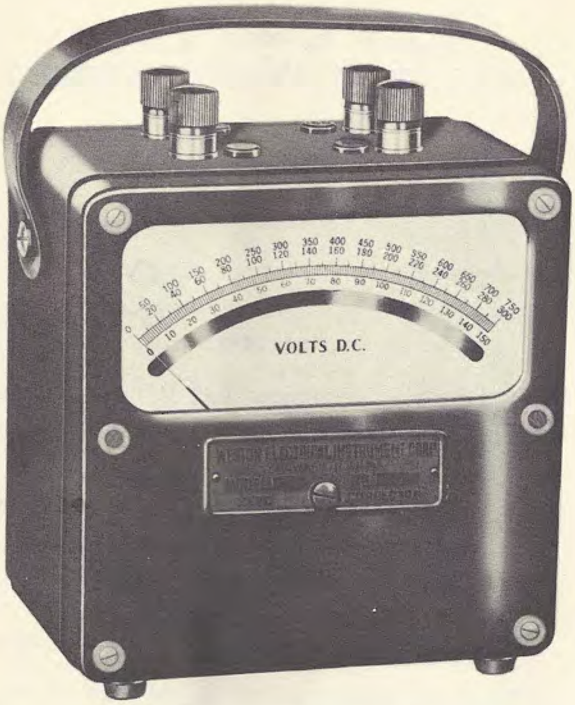
11-3. COMMERCIAL METER MOVEMENTS

A typical commercial meter is shown in Fig. 11-5*a*. A skeleton view of the movement of the same meter is shown in Fig. 11-5*b*. Most of the parts shown have been described already. However, let us discuss the zero-adjusting device, the needle or pointer, the needle stops, and the case or container for the movement.

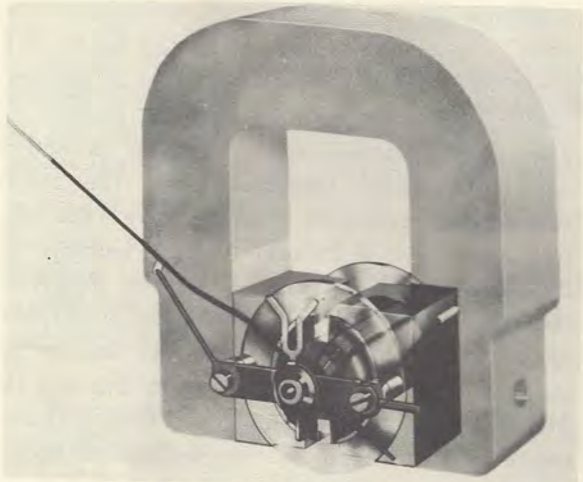
The zero-adjusting device is used to bring the meter needle over the zero mark on the meter scale. This adjustment is made by turning the zero-adjust screw-head on the front panel of the meter until the meter needle is in the proper position. The screw-head that is turned is actually the slotted head of the adjusting rod. This adjusting rod is connected with the bracket that holds the moving coil. The bracket and the coil are connected with springs. When the adjusting rod is turned, it moves the bracket and the coil. Therefore, the meter needle moves. Once the needle is so adjusted, this adjustment seldom has to be made again, unless the meter is roughly handled or driven hard off scale.

The needle, or pointer, is usually a very light tubular shaft made of an aluminum alloy. The part of the needle that actually extends over the dial scales has a thin knife-blade shape to permit accurate reading. Sometimes the blade-shaped portion of the pointer is a separate piece fastened to the tubular shaft. This piece, called the blade, is often made extra wide in order to increase the air resistance that the needle meets in swinging through the narrow space between the scale card and the protective glass. This air resistance adds some mechanical damping to help control overswing of the needle.

The stops in practical meters are usually two wire brackets fastened to the movement in such a way that they mechanically stop the needle from swinging more than a few degrees off scale in either direction. These stops are usually padded; a piece of rubber or other insulating tubing is slipped over the part that actually meets the needle to minimize wear and shock to the movement when needle is pinned by reversed polarity or too much current.



(a)



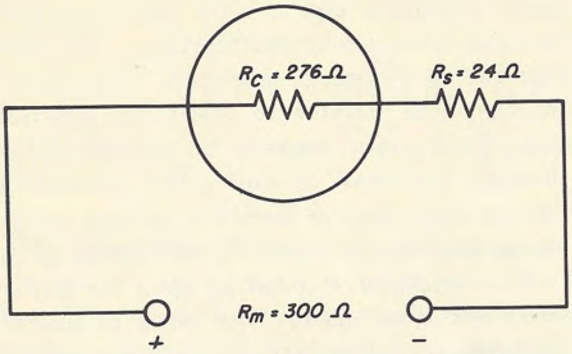
(b)

Fig. 11-5

In most practical commercial meters, the entire movement is mounted in a plastic or metal case. The face is visible through a window of glass or plastic. This aids in protecting the movement from dust, heat, and tampering, improves the appearance of the meter, and makes it more convenient to mount the movement.

Sensitivity. Useful as a simple moving-coil meter may be, it is far *more* useful when combined with certain parts, such as resistors, switches, and rectifiers. We know that the basic meter movement is designed to move the pointer to full-scale position when a certain amount of current flows through the moving coil. The amount of current necessary to force the pointer to full scale may be in amperes, milliamperes, or in microamperes, depending upon the sensitivity of the movement. Your meter movement, for example, needs only 50 microamperes to go full scale. However, many multimeters use a basic 1-ma movement. With such a movement, the pointer is at full scale when a current of 1 ma flows through the moving coil. Of course, a voltage must be placed across the moving coil for a current to flow. The amount of voltage depends on the resistance of the coil.

Meter Resistance. Because it is difficult to make two coils exactly alike, the resistance of one moving coil may not be the same as the resistance of the next coil made by the same operator for the same meter model. The difference in resistance may be only an ohm or two, or it may be as much as twenty or thirty ohms. In order that all meter movements of the same model have the same resistance, it is necessary to add some resistance in series with the moving coil to bring the total resistance up to some standard amount. For example, Fig. 11-6*a* shows a meter with a moving coil resistance (R_c) of 276 ohms. The standard resistance for this meter model has been set at 300 ohms. To bring this movement up to the standard, it is necessary to add a 24-ohm resistor. This resistor is called the *standardizing resistor* and is marked R_s in the drawing. However, the meter movement shown in Fig. 11-6*b* has a 281-ohm moving coil. The standardizing resistor for this movement has a value of 19 ohms. Not all 1-ma movements have a standard resistance of 300 ohms; the standard varies with different models and different manufacturers. Neither do all meter movements meet an exact standard of resistance. Some meter movements may vary slightly from the standard. However, because meter accuracy is affected by several factors in addition to



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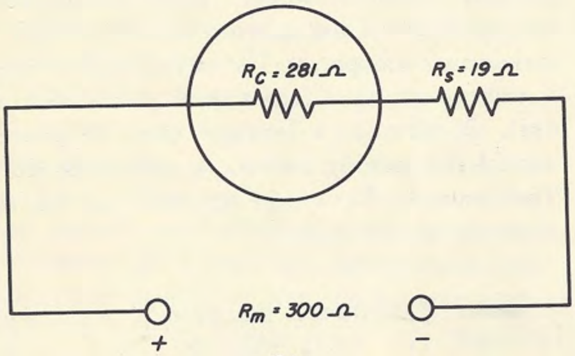


(b)

Fig. 11-6

the coil resistance, most manufacturers try to get the meter resistance as close to the standard as possible.

11-4. MOVEMENT USED AS VOLTMETER

Calculating Multipliers. If a 1-ma movement with 300 ohms resistance has 1-ma of current flowing at full scale, the voltage across the meter terminals may be found by using Ohm's Law:

$$E_m = I_m \times R_m$$
$$= 0.001 \times 300$$
$$= 0.3 \text{ volts}$$

where:

E_m = voltage across meter terminals

I_m = current through meter

R_m = total resistance of moving coil and standardizing resistor

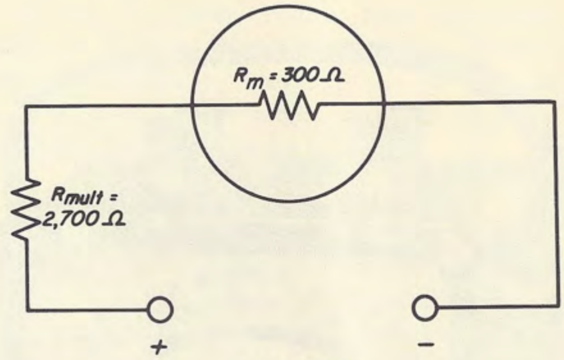


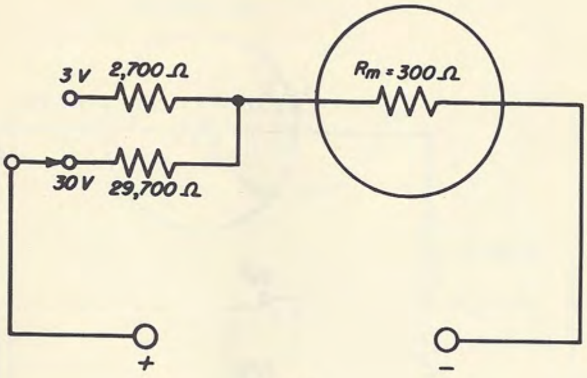
Fig. 11-7

If the same movement has 0.5 ma flowing through it, the voltage across the terminal is:

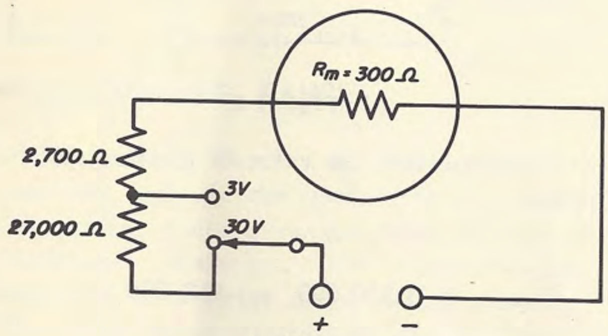
$$E_m = I_m \times R_m$$
$$= 0.0005 \times 300$$
$$= 0.15 \text{ volts}$$

Thus, the meter measures not only current but voltage, too. To read voltage, all that is necessary is to calibrate the dial for voltage readings as well as current readings. However, a meter that measures only up to 0.3 volts is not of very much use to a serviceman. The voltage limit can be raised by placing a current-limiting resistor in series with the meter movement and the meter terminals. Figure 11-7 shows how this may be done. Such a current-limiting resistor is called a *multiplier* and is marked R_{mult} in the drawing. The value of the multiplier resistor is determined by the amount of voltage that is measured when the needle goes to full scale. The total series resistance of the meter and the multiplier added together must permit exactly 1 ma to flow. For example, if the full scale reading is to be 3 volts, then the total resistance (R_t) of the meter and the multiplier is found by using Ohm's Law:

$$R_t = \frac{E}{I_m}$$
$$= \frac{3}{0.001}$$
$$= 3000 \text{ ohms}$$



(a)



(b)

Fig. 11-8

If the total resistance of the meter and multiplier is 3,000 ohms, then the resistance of the multiplier is equal to 3,000 ohms *minus* the 300 ohms of the meter resistance, or 2,700 ohms (3,000 − 300 = 2,700). The circuit, as you can see in Fig. 11-7, is really a voltage divider. The meter, at full scale, has a voltage drop of 0.3 volt and the multiplier has a drop of 2.7 volts.

To increase the voltage range to 30 volts, we find R_t as follows:

$$R_t = \frac{30}{0.001}$$

$$= 30{,}000 \text{ ohms}$$

Then:

$$R_{mult} = R_t - R_m$$

$$= 30{,}000 - 300$$

$$= 29{,}700 \text{ ohms}$$

We could then hook up the meter circuit as shown in Fig. 11-8*a*. This would give us two useful voltage scales: 3 volts and 30 volts. However, a more practical method would permit us to use the 3-volt multiplier as part of the resistance of the 30-volt multiplier. This arrangement is shown in Fig. 11-8*b*. To find the value of resistance needed for the second multiplier, we subtract the sum of the meter resistance and the first multiplier from the total resistance of the 30-volt range:

$$30{,}000 - (300 + 2{,}700)$$

$$30{,}000 - 3{,}000 = 27{,}000 \text{ ohms}$$

As shown in the drawing, when the switch is in the 3-volt position, only the meter resistance and 2,700-ohm multiplier are in the circuit. When the switch is in the 30-volt position, the meter resistance, the 2,700-ohm multiplier, and the 27,000-ohm multiplier are all in series.

The voltage range may be extended to any reasonable value by making the following calculations:

1. Find the total resistance. The total

$$\text{resistance} = \frac{\text{full-scale voltage desired}}{\text{full-scale meter current}}$$

2. Subtract the sum of the meter resistance and the total multiplier resistance (of the next scale lower) from the total resistance. The remainder equals the value of the new multiplier.

For example, to increase the voltage range of the meter from 30 volts to 150 volts, we first find the total resistance:

$$R_t = \frac{150}{0.001}$$

$$= 150{,}000 \text{ ohms}$$

Next we find the value of the new multiplier:

$$R_{mult} = R_t - (R_m + \text{total multiplier resistance})$$
$$= 150{,}000 - 30{,}000$$
$$= 120{,}000 \text{ ohms}$$

Figure 11-9 shows the new multiplier connected to the meter circuit.

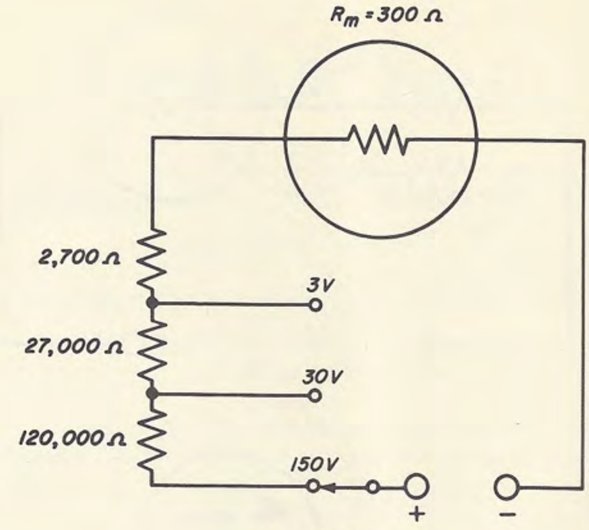


Fig. 11-9

Have you noticed that for the 3-volt range the total resistance was 3,000 ohms, for the 30-volt range it was 30,000 ohms, and for the 150-volt range it was 150,000 ohms? In each case the total resistance was equal to a thousand ohms for each volt of full-scale reading. For this reason, the sensitivity of meters that use a 1-ma movement is spoken of as being a thousand ohms per volt. To find the ohms-per-volt sensitivity of a meter, divide one volt by the amount of current necessary to drive the needle to full scale. For example, the meter in your multimeter is rated at 50 ua. To find the ohms-per-volt sensitivity, divide 1 by 0.00005a and get 20,000 ohms. Your meter, therefore, has a sensitivity rating of 20,000 ohms per volt.

High-Voltage Ranges. When voltage ranges above about 1,000 volts are made part of a meter, it is common practice to keep these high potentials away from the selector switch. This is done to prevent possible *arcing over* in the switch. (You know that when electrical pressure becomes great enough, electrons actually jump across from one terminal to another. We sometimes call this arcing over.) In such cases, as shown in Fig. 11-10, the positive test lead connects to a separate jack or terminal post that is connected directly to the high-voltage multiplier to take advantage of the air space between the post and switch lug.

To increase the voltage range of the meter from 150 volts to 1,500 volts, we must first find the total resistance, as before:

$$R_t = \frac{1{,}500}{0.001} = 1{,}500{,}000 \text{ ohms}$$

Next we find the value of the new multiplier:

$$R_{mult} = 1{,}500{,}000 - 150{,}000$$
$$= 1{,}350{,}000 \text{ ohms}$$

In addition to the use of special high-voltage jacks, high-voltage ranges call for special high-voltage test leads that have probes and test lead wire that can withstand the high potentials. Further instructions for making high-voltaxe tests are given in Service Practices 7.

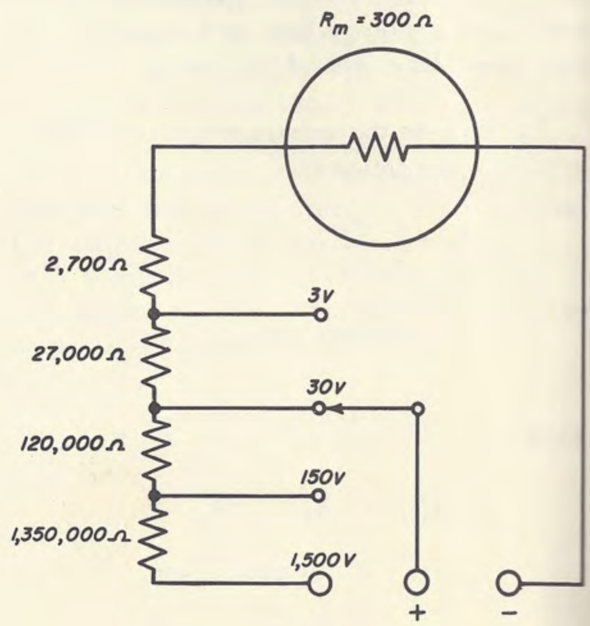


Fig. 11-10

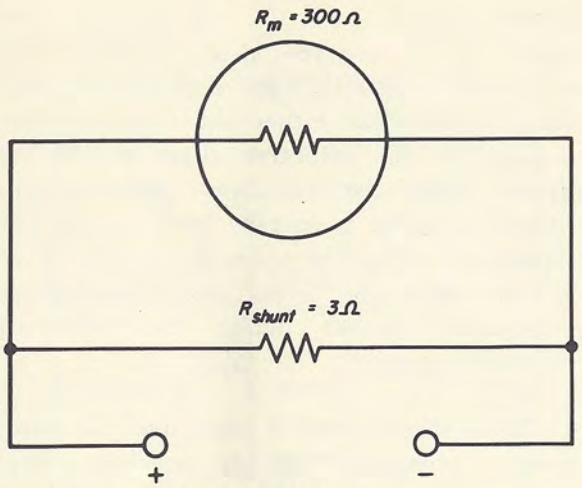


Fig. 11-11

11-5. CURRENT RANGES

Calculating Shunts. We have seen how we may increase the usefulness of a meter by adding voltage ranges with the aid of multiplier resistors. The current-reading capacity of a meter may also be increased by using *shunt-resistors* or *shunts*. Shunts are resistors in parallel with the meter movement. For example, in Fig. 11-11, a 3-ohm resistor is connected in parallel with a 300-ohm, 1-ma movement. As you know, the greater the resistance, the less is the current; and the less the resistance, the greater is the current. So, any current entering at the negative meter jack and leaving at the positive meter jack will divide between the meter and the shunt resistor, with the greater part going through the low-value shunt resistor. In fact, we can calculate exactly how much will flow in each, because the current will be in inverse proportion to the proportion of the meter resistance over the shunt resistance. The proportion of the meter resistance to the shunt resistance is:

$$\frac{300 \text{ meter resistance)}}{3 \text{ (shunt resistance)}} = \frac{100}{1}$$

Inverted, this becomes:

$$\frac{1}{100} = \frac{\text{meter current}}{\text{shunt current}}$$

Therefore, at full scale the meter current is 1 ma, and the shunt current is 100 ma. The total current flowing through the meter and the shunt will be the sum of these, or 101 ma. Normally, we wouldn't have a 101-range. Usually, the value of a current range is rounded off to even zeroes or, in some cases, to multiples of five. So we might have ranges of 10, 20, and 100 ma, or 5, 10, 25, and 100 ma.

The calculation of the shunt resistance needed for any current range is easy to find if the full-scale current and the internal resistance of the meter are known. We use the formula:

$$R_{\text{shunt}} = \frac{R_m}{N-1}$$

where:

R_m = meter resistance

N = number of times meter current is multiplied for new current range

To use this formula, we must first decide what current range we want so that we may know how much N is. For example, let's find the value of shunt needed for a 10-ma range. Ten milliamperes is ten times one milliampere (the full-scale meter current), so N equals 10. Therefore, we divide the meter resistance by 10 minus 1. The number 1 is constant and remains the same, regardless of the full-scale meter current.

$$R_{\text{shunt}} = \frac{R_m}{N-1}$$

$$= \frac{300}{10-1}$$

$$= \frac{300}{9}$$

$$= 33\text{-}1/3 \text{ ohms}$$

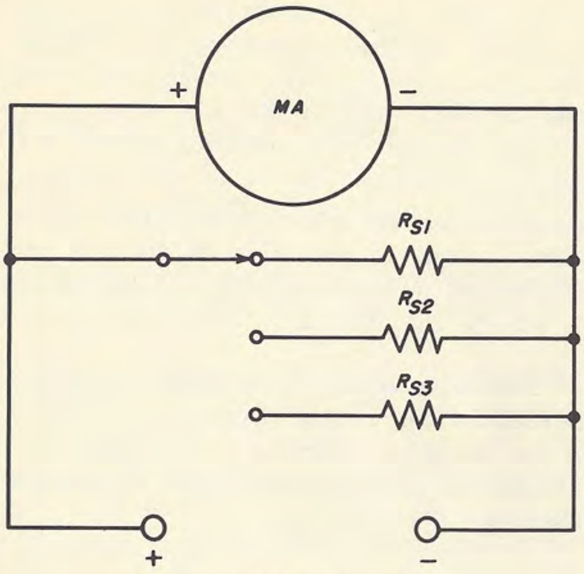


Fig. 11-12

To find the shunt necessary to measure 100 ma full-scale:

$$R_{\text{shunt}} = \frac{R_m}{N - 1}$$

$$= \frac{300}{100 - 1}$$

$$= \frac{300}{99}$$

$$= 3\text{-}1/33 \text{ ohms}$$

We have a choice of switching methods for adding shunt resistors to the meter. It is possible to use the very simple method shown in Fig. 11-12, but this method has certain serious practical disadvantages that make us look for a better way.

Consider what happens in the circuit when the switch arm is moved from one shunt resistor to another. While the arm is between contacts, the entire current flows through the meter only, and the meter may be damaged if the current exceeds the full-scale capacity of the meter movement. A switch of the *make-before-break* type can be used. When such a switch is used, the contact arm makes connection with the next shunt before breaking connection with the shunt from which it moves. So, for a short time, while the switch is changing to another current range, both the old and the new shunt are across the meter. Because two resistors in parallel have a combined value that is less than either shunt resistor has separately, the effective shunt across the meter during the switching operation will cause the meter to receive less current than it would in either the old or the new position. In this way, the meter is protected from excessive current during the switching operation.

While this method is often used, it sometimes presents another problem. When switches have been in service a while, a small amount of resistance, called *contact resistance*, may appear between the contact arm and any switch point. The resistance is caused by oxidation of the metal surfaces of the switch and, sometimes, by dust and dirt. If the resistance of the shunt is very low, the contact resistance between the arm and the switch points may cause serious errors in the reading. This is true because the contact resistance is in series with the shunt, and thus adds to the actual resistance across the meter. This difficulty can be overcome by using a two-gang switch, as shown in Fig. 11-13. In this circuit, the contact resistance at *4A* has no effect on the value of shunt R_{S4}, and the contact resistance at *4B* is in series with the resistance

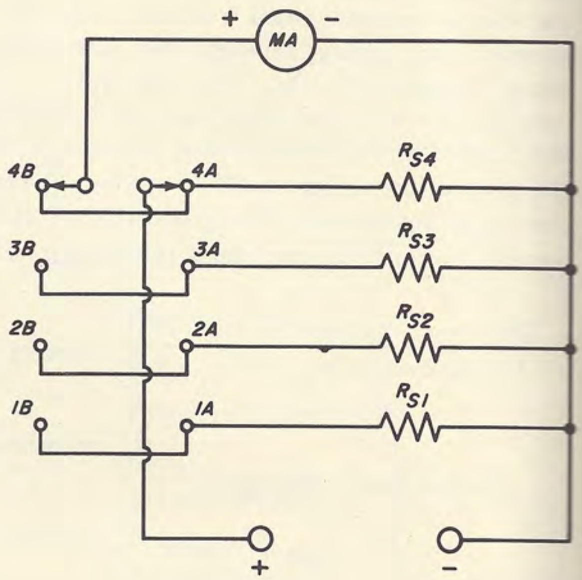


Fig. 11-13

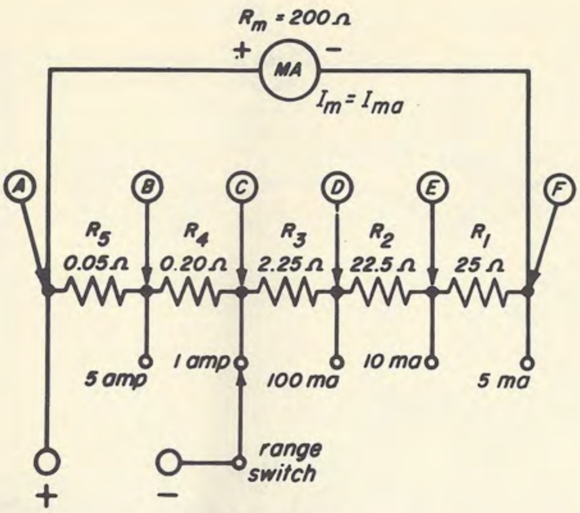


Fig. 11-14

of the meter movement. Because the meter résistance is much greater than the contact resistance, it does not cause any serious error.

Universal Shunt. Another method of connecting shunt resistors is known as the *universal shunt.* Figure 11-14 shows a typical universal shunt and switching system. Note that the resistors are all connected in series across the meter terminals and the line connection goes to the switch arm. Current from the line must go through the switch contact before it can reach the meter. If the switch contact fails, no current can reach the meter. But in the simple shunt of Fig. 11-12, if the switch contact fails while a measurement is being made, no current goes goes through the shunt, thus letting the entire current flow through the meter. This may result in meter damage. Thus, this feature of meter protection is an important advantage of the universal shunt. To calculate the proper values of the universal shunt, we must know the meter current needed for full-scale deflection, the meter resistance, and the current ranges needed. It is not possible to make a meter that needs 50 microamperes for full-scale deflection read full scale on 10 microamperes, so any new current ranges must be greater than the basic current range of the meter. Let's find the value of shunts needed if a 1-ma movement with a resistance of 200 ohms is to read full scale on 5 ma, 10 ma, 100 ma, 1 amp, and 5 amps. Since the lowest current range is to be 5 ma, and the meter requires 1/5 of this current (1 ma) for full-scale deflection, the other 4/5 (4 ma) must pass through the shunt. We will assume that the meter resistance is 200 ohms. To find the value of this shunt, we use the formula:

$$R_{shunt} = \frac{R_m}{N-1}$$

$$= \frac{200}{5-1}$$

$$= 50 \text{ ohms}$$

The total series resistance of a universal shunt is always equal to the resistance of the shunt needed for the *lowest* current range. The current ranges of any practical ammeter are all multiples of the full-scale current of the basic meter movement. For example, take the five ranges we selected for the 1-ma movement: 5 ma is five times, 10 ma is ten times, 100 ma is 100 times, 1 ampere is 1,000 times, and 5 amperes is 5,000 times the basic meter current. We call these *multiplying factors.* We use them to find the value of each of the shunt sections. We use the formula:

$$R_{section} = \frac{R_{shunt} + R_{meter}}{N}$$

where:

N = multiplying factor for the meter range

R_{shunt} = total shunt resistance across meter

Let's find the value of the 10-ma section of the shunt:

$$R_{10\ ma} = \frac{50 + 200}{10}$$

$$= \frac{250}{10}$$

$$= 25 \text{ ohms}$$

The 100-ma section comes next:

$$R_{100\ ma} = \frac{50 + 200}{100}$$

$$= \frac{250}{100}$$

$$= 2.5 \text{ ohms}$$

The 1-amp section follows:

$$R_{1\ amp} = \frac{50 + 200}{1,000}$$

$$= \frac{250}{1,000}$$

$$= 0.25 \text{ ohm}$$

And finally the 5-amp section:

$$R_{5\ amp} = \frac{50 + 200}{5,000}$$

$$= \frac{250}{5,000}$$

$$= 0.05 \text{ ohm}$$

The resistance values we have just found show the actual value of shunt resistance across the input terminals for each current range. For example, when the range switch is in the 5-ma position, the entire 50-ohm shunt, *A-F*, is used. We found that the shunt for the 10 ma range is 25 ohms, so we find that when the switch is in the 10 ma position, 25 ohms is across the input terminals, *A-E*. To find the value of the first section, R_1, we subtract the 25 ohms of the 10 ma section from the 50 ohms of the total shunt and get 25 ohms. The first section, R_1, is therefore 25 ohms.

The 25 ohms that we use for the 10-ma shunt is divided into four sections for the remaining ranges. Therefore, to find R_2 (*D-E*), we subtract the 2.5 ohms of the 100-ma range from 25 ohms and get 22.5 ohms, the value of R_2. To find R_3 *(C-D)*, we subtract the 0.25 ohm of the 1-amp range from 2.5 ohms of the 100 ma range and get 2.25 ohms. To find R_4 *(B-C)* we subtract the 0.05 ohm of the 5-amp range from 0.25 ohm of the 1-amp range and get 0.20 ohm.

11-6. OHMMETER CIRCUITS

A moving-coil meter may be used to measure resistance, if a source of current is available. A simple ohmmeter circuit is shown in Fig. 11-15. It consists of a 1-ma

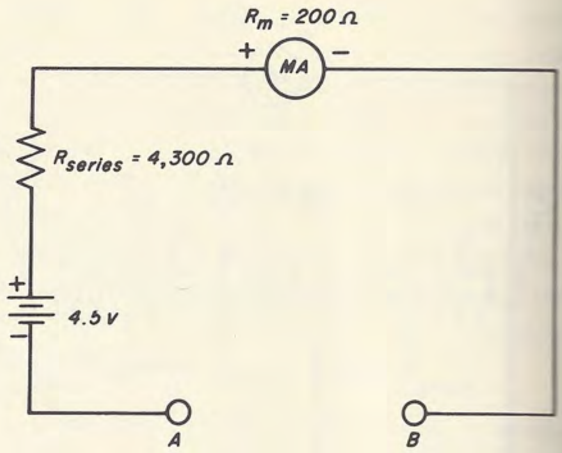


Fig. 11-15

meter in series with a current-limiting resistor and a 4.5-volt battery. The internal resistance of the meter is 200 ohms. The series resistor has a resistance of 4,300 ohms. This value was chosen so that the resistance of the meter added to the resistance of the series resistor would be just enough to limit the current flow to exactly 1 ma when connected across 4.5 volts. It was found by using Ohm's Law:

$$R_t = \frac{E}{I}$$

$$= \frac{4.5}{0.001}$$

$$= 4,500 \text{ ohms}$$

then:

$$R_{series} = R_t - R_m$$

$$= 4,500 - 200$$

$$= 4,300 \text{ ohms}$$

If a wire of zero resistance is placed across terminals *A* and *B* in Fig. 11-15, exactly 1 ma will flow and the pointer will go to full scale. Therefore, an ohmmeter scale is marked zero ohms at the full-scale position and infinity (∞) at the zero-current position. When a resistor of unknown value (R_x) is placed across terminals *A* and *B*, the total series resistance is equal to 4,500 ohms added to resistance of R_x. *The* current is then less than one ma and the pointer does not go to full scale. For example, let's

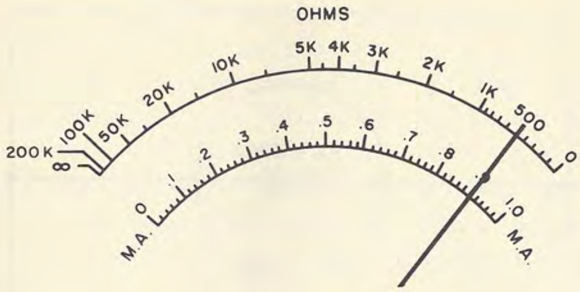


Fig. 11-16

assume that R_X equals 500 ohms. Then the total series resistance equals 5000 ohms. The current flowing through the meter is then 4.5 divided by 5,000 which equals 0.9 ma. Therefore, when the pointer rests on the 0.9 ma line on the meter scale, as shown in Fig. 11-16, it also rests on the 500-ohm line on the ohmmeter scale. If we now add another 500-ohms, making R_X 1,000 ohms, the total resistance becomes 5,500 ohms and the current is reduced to 0.818 ma. If we make R_X 1,500 ohms, the total resistance becomes 6,000 ohms and the current is reduced to 0.75 ma. When we add equal amounts of resistance, one after the other, it soon becomes clear that the movement of the meter pointer is not equal for each equal change in resistance. In other words, the typical ohmmeter scale is not linear.

In all practical ohmmeters, a rheostat makes up part of the series resistance. You remember, from your study of cells and batteries, that, as a cell becomes old and used up, the voltage delivered to a load (terminal voltage) drops below the rated value. When the terminal voltage of a cell used in an ohmmeter drops below its rated value, the series resistance is reduced by adjusting the series rheostat until the current flowing through the meter permits the needle to go to full scale. For example, if the battery voltage should drop to 4.2 volts, the total resistance needed to produce a current flow of 1 ma would be only 4,200 ohms. Therefore, the series resistor would need to be only 4,000 ohms instead of the 4,300 ohms necessary when the batteries are at

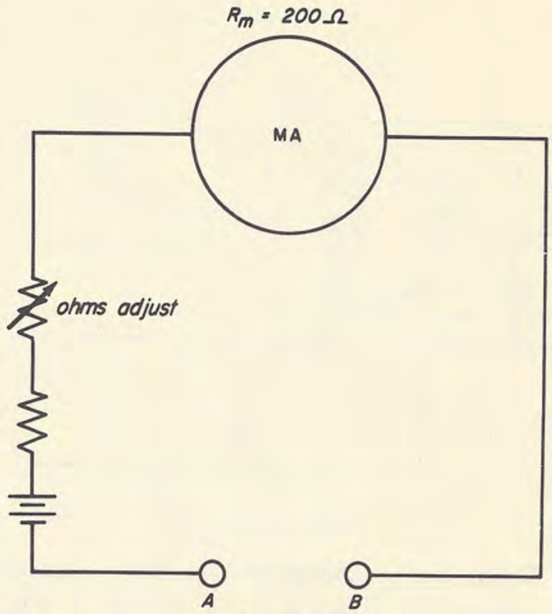


Fig. 11-17

full strength. Figure 11-17 shows the series resistor divided into two parts, one fixed and the other variable. The variable resistor is usually called the *ohms adjust* or *zero ohms* control.

In the instructions for reading meters given in Service Practices 7, you were told that ohmmeter readings near the center of the scale are most accurate. For this reason, most ohmmeters have two or more ranges. For example, if a second ohmmeter range were provided for your meter, with a multiplier factor of 10, then the pointer would rest at the half-scale position when a 45,000-ohm resistor was being measured. The scale shown in Fig. 11-16 would be used, with the difference that all readings would be multiplied by 10.

To provide such an ohmmeter range, the circuit shown in Fig. 11-18 might be used. Looking at the diagram, you can see that it would be necessary to change to a 45-volt battery and to increase the series resistance to 44,800 ohms. You can also see that if we wanted to add a 10-times higher range, it would be necessary to have 450 volts and a series resistor of 449,800 ohms. Such a meter would read 450,000 ohms at half-scale. However, because of the high voltages required, this method of providing several ohmmeter ranges is not practical.

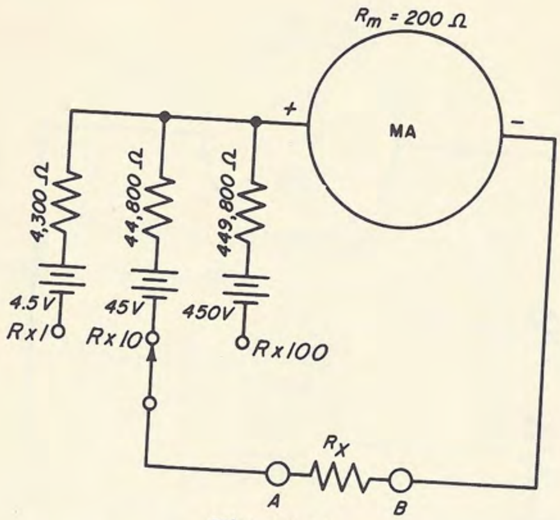


Fig. 11-18

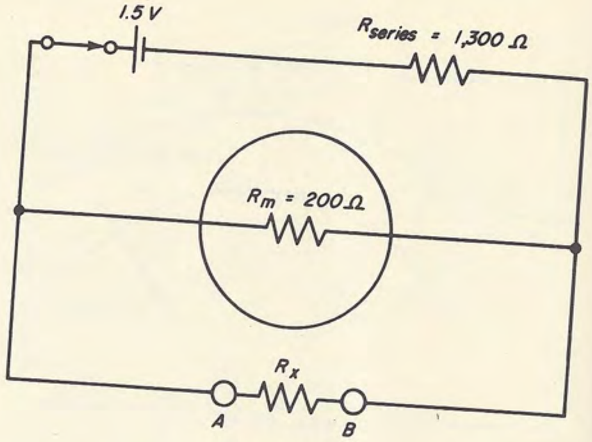


Fig. 11-19

Shunt-Type Ohmmeter. Another method of measuring resistance is shown in Fig. 11-19. It is called the *shunt-type ohmmeter* because the resistor being measured is placed in shunt with the meter movement. It uses a 1.5-volt dry cell instead of the 4.5-volt battery used in the other circuit. All that is necessary is to find the resistance that permits the flow of 1 ma when 1.5 volts is applied. From this, we subtract the resistance of the meter and the remainder is the resistance of the series resistor.

The operation of this circuit is simple. When the switch is closed, the needle reads full scale (infinity on the ohms scale). If terminals *A* and *B* are connected together with a wire, the meter is shorted out and the pointer will remain in the zero-current position, which reads zero on the ohms scale. This ohmmeter reads in a direction opposite to that of the series type discussed before; the low values of resistance are indicated on the left side of the dial and the high values on the right side. When a resistor is is placed between *A* and *B*, the current divides; part goes through the resistor and part through the meter. For example, if R_x is equal to the meter resistance, half the current flows through the meter and half through R_x. The total current is 1 ma; therefore, the current of 0.5 ma flowing through the meter moves the pointer to half scale. When R_x equals 50 ohms, 4/5 of the current will flow through R_x and 1/5 through the meter. The pointer, therefore, will rest on the 0.2-ma calibration line.

A meter scale may be calculated for such an ohmmeter by using the formula:

$$I_m = \frac{R_x}{R_x + R_m} \times I_{fs}$$

where:

I_m = the position of the pointer on current scale

R_x = resistance of the resistor being measured

R_m = the meter resistance

I_{fs} = the current necessary for full-scale reading in amperes

For example, if the resistance of R_x is 400 ohms, then:

$$I_m = \frac{400}{400 + 200} \times 0.001$$

$$= \frac{400}{600} \times 0.001$$

$$= \frac{2}{3} \times 0.001$$

$$= 0.00067 \text{ amp. or } 0.67 \text{ ma}$$

The above formula is accurate enough for most purposes. But there is a slight error due to the fact that the total series resistance in the meter circuit changes whenever a resistor to be measured is placed in parallel with the meter. This error is greatest when very low values of resistance are being measured. The error can be eliminated by use of a more complex, but accurate formula:

$$I_m = \frac{R_m + R_{series}}{R_m + R_{series} + \dfrac{R_m \times R_{series}}{R_x}} \times I_{fs}$$

where:

I_m = position of pointer on current scale

R_m = meter resistance

R_{series} = resistance of current-limiting resistor in series with meter

R_x = resistance of resistor being measured

I_{fs} = current necessary for full-scale reading in amperes

For example, let R_x = 4,500 ohms; then:

$$I_m = \frac{200 + 1{,}300}{200 + 1{,}300 + \dfrac{200 \times 1{,}300}{4{,}500}} \times 0.001$$

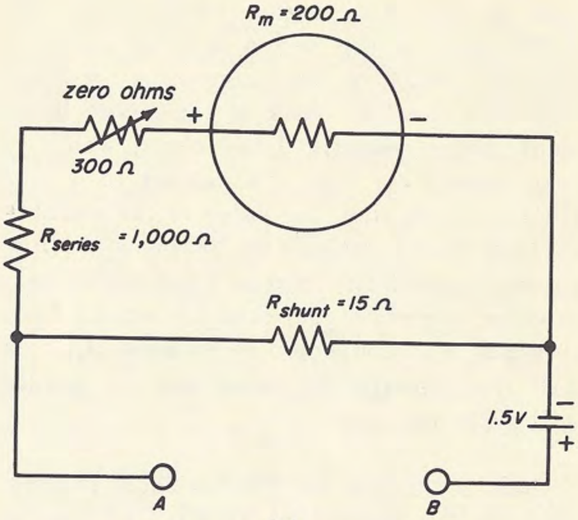
$$= \frac{1{,}500}{1{,}500 + \dfrac{260{,}000}{4{,}500}} \times 0.001$$

$$= \frac{1{,}500}{1{,}500 + 57.7} \times 0.001$$

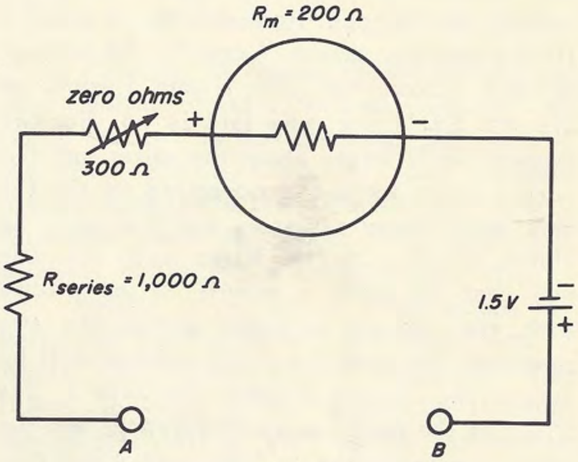
$$= \frac{1{,}500}{1{,}558} \times 0.001$$

$$= 0.00096 \text{ amp or } 0.96 \text{ ma}$$

This form of ohmmeter has one serious disadvantage; whenever the selector switch is connected to such a range, the meter draws current. If the switch is left on, the meter may use up the battery before someone remembers to change the switch position.



(a)



(b)

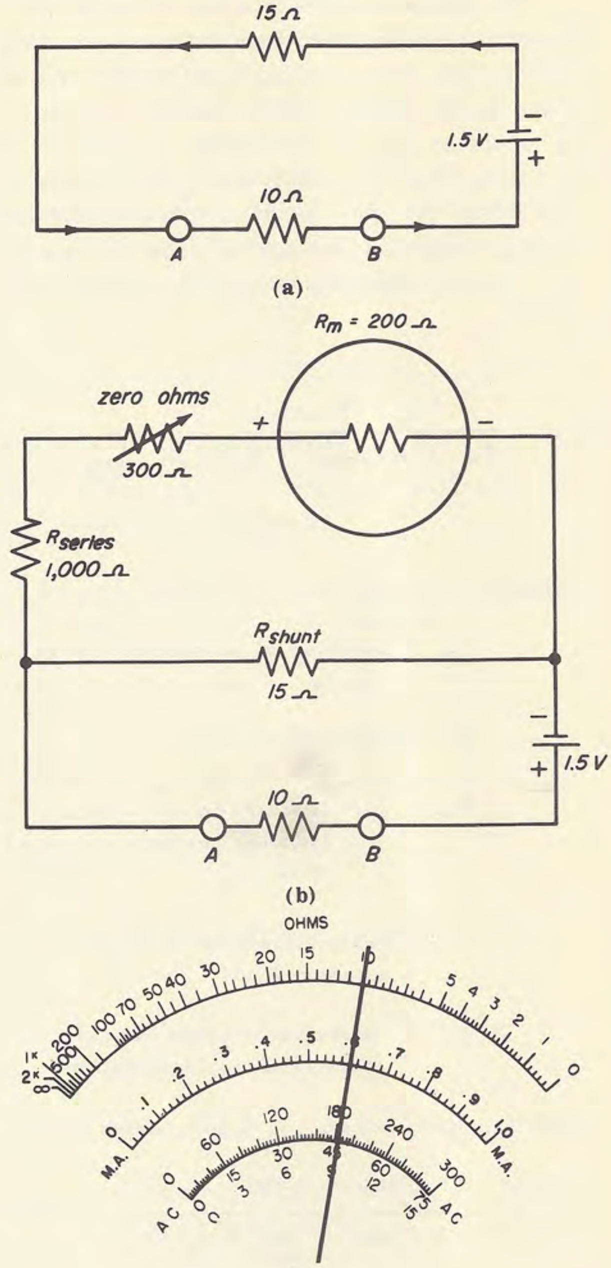
Fig. 11-20

Voltage-Divider Ohmmeter. Another type of ohmmeter, sometimes called a voltage-divider ohmmeter, reads in the same direction as the series-type ohmmeter and has calibrations that are more nearly linear than either of the types just discussed. Figure 11-20*a* shows the basic circuit. Because the same circuit is used in the ohmmeter section of your multimeter, you should know how it works, At first glance, it looks complicated, but it isn't really – as you will see. Let's take the circuit apart and see what each part does. In Fig. 11-20*b*, we have left out the 15-ohm shunt resistor so that we can look at the rest of the circuit first. The 1,000 ohms of the series resistor added to the 300 ohms of the zero-ohms resistor added to the 200 ohms of the meter movement makes exactly 1,500 ohms, which is just enough to limit the current to 1 ma. (In actual practice, the value of the variable resistor would probably be 500 ohms to allow for the possibility that a fresh cell might produce slightly higher than 1.5 volts.) When terminal *A* is connected to terminal *B*, 1 ma will flow through the meter and the needle will go to full scale.

Now let us put the 15-ohm shunt resistor back in the circuit, as in Fig. 11-20*a*. So long as the circuit remains open at *A* and *B*, nothing will happen. However, let us place a 10-ohm resistor across *A* and *B*. The voltage divides across the 10-ohm and 15-ohm resistors. Let's see why this is so. For the moment we'll forget about the meter and the series resistors and concentrate on the 15-ohm and 10-ohm resistors and the cell, as shown in Fig. 11-21*a*. Right away you can see that we have a simple series circuit with the voltage divided across the two resistors. Three-fifths of the voltage will be across the 15-ohm resistor (because it has 15/25 of the total series resistance) and the remaining two-fifths will be across the ten-ohm resistor. So, 0.9 volt will appear across the 15-ohm resistor and 0.6 volt across the 10-ohm resistor.

Let's put the meter and series resistors back in the circuit, as in Fig. 11-21*b*. Remember that 0.9 volt appears across the meter circuit. The needle can no longer go to full scale. Instead it will go only 3/5 of the way, as in Fig. 11-21*c*. On the ohms scale, this is shown as the 10-ohm calibration point.

If we place a 15-ohm resistor across *A* and *B*, then the voltage will divide evenly across each of the 15-ohm resistors, the meter will receive half the full-scale current, and the needle will come to rest at the middle of the scale. Therefore, the 15-ohm calibration is at half-scale.



(c)

Fig. 11-21

We can go on and calibrate the entire ohmmeter scale by placing standard values across terminals *A* and *B* and figuring how much of the voltage will appear across the 15-ohm shunt resistor. Naturally the calibrations are crowded together at the left-hand side of the scale. So, if we wanted to add an *R* x 100 range, it would seem that we would just multiply the 15 ohms of the shunt resistor by 100 and get 1,500 ohms. But it wouldn't work. Let's see why this is so.

First let's go back to the circuit with

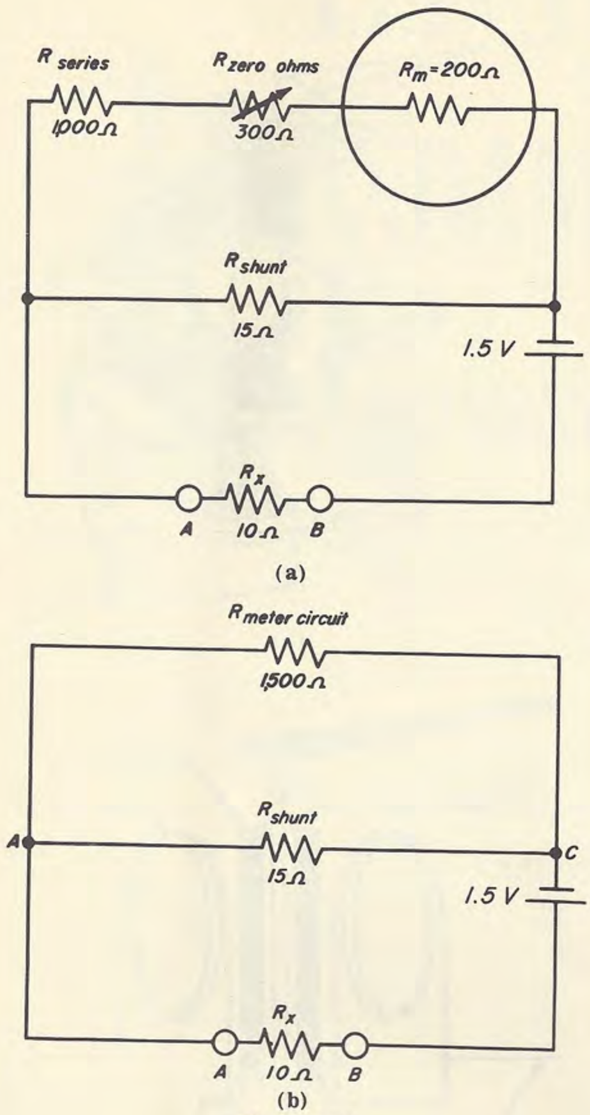


Fig. 11-22

the 15-ohm shunt in it. As before, we'll place a 10-ohm resistor across terminals *A* and *B*. Figure 11-22*a* shows the circuit and the resistance of each unit in the circuit. We can see that the meter circuit has a total of 1,500 ohms resistance. So, in Fig. 11-22*b*, this part of the circuit is shown as a single resistor of 1,500 ohms. In this simplified drawing of the circuit, we can see that the 1,500 ohms of the meter is actually in parallel with the 15-ohm shunt resistor. Therefore the amount of resistance between *A* and *C* is slightly less than 15 ohms. However, from your study of d-c circuits and meter loading, you know that when two resistors are in parallel, and one has more than ten times the resistance of the other, the total resistance of the two in parallel is practically the same as the resistance of the one with the smaller resistance. In the case of our ohmmeter circuit, the meter circuit resistance is 100 times the resistance of the 15-ohm shunt, so for practical purposes we can say that the resistance between *A* and *C* is 15 ohms. But if we place a 1,500-ohm shunt instead of the 15-ohm shunt, we will have 1,500 ohms in parallel with 1,500 ohms. With a little figuring, we can see that the resistance of these two in parallel is 750 ohms. As a result, we would not get an *R* x 100 range but would get an *R* x 50 range instead. So, normally, we would shift to simple series-resistor ohmmeter circuits for the higher ranges and use the voltage-divider circuit only for the low ohms range.

In choosing the value of the shunt used in the voltage divider, we must consider two facts. One fact is that the lower the value of the shunt that is used, the more accurate are the readings of low values of resistance. Whatever value we choose will determine what the half-scale calibration point will be. For example, if we use a 5-ohm shunt, the half-scale calibration will be 5 ohms. Here's where the second factor comes in. The lower the value of the shunt that is used, the greater will be the load on the cell or battery that powers the ohmmeter. So, normally we select a value of shunt that draws a reasonable amount of current from the cell or battery.

11-7. POWER MEASUREMENT

The amount of d-c power consumed in a load, such as an electric heater or lamp, may be found by measuring the voltage across the load and the current flowing through the load and multiplying the values together. However, it is possible to make a meter that does this directly. With such a meter, called an *electrodynamometer-type wattmeter,* we can read the power in watts directly from the meter dial without arithmetic and separate voltage and current measurements. A typical wattmeter, calibra-

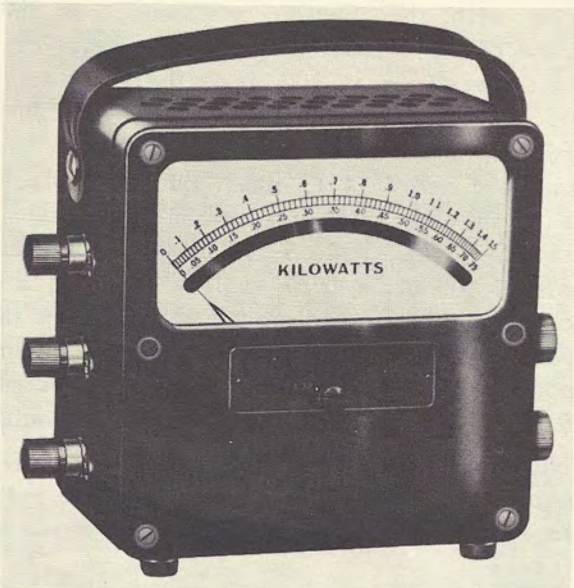
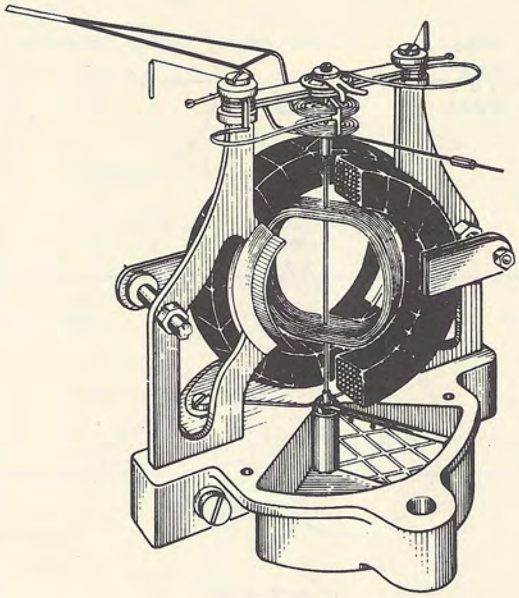


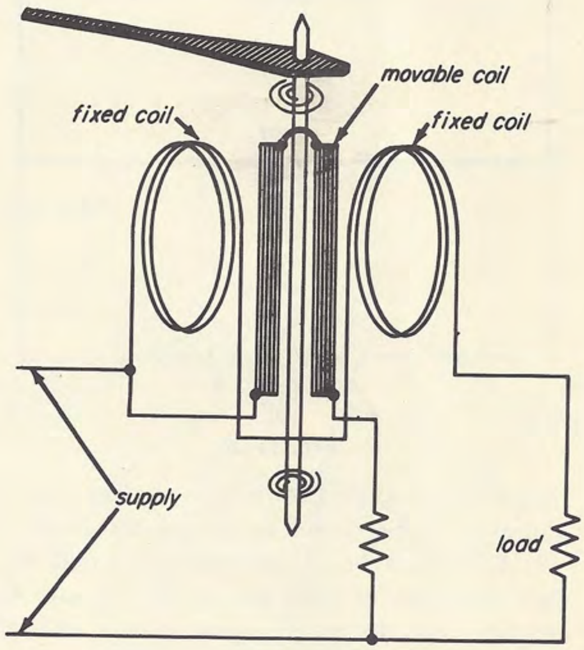
Fig. 11-23

ted in kilowatts, is shown in Fig. 11-23.

In the meters discussed so far, the field has been supplied by a permanent magnet, so that only the changes in the current flowing through the moving coil caused changes in the movement of the needle. The electrodynamometer does not use a permanent magnet. Instead, a fixed coil carrying current provides the field for the moving coil. Figure 11-24*a* shows a cutaway view of the basic movement. As you can see, the fixed coil is divided into two parts, one on each side of the moving coil. The current flowing in the load flows through the fixed coil and provides the field for the moving coil. As shown in Fig. 11-24*b*, the voltage across the load is connected through a high-value resistor (multiplier) to the moving coil. With these connections, the field set up by the fixed coil is in proportion to the current and the field set up by the moving coil is in proportion to the voltage. The two fields combine to force the needle to a position of the calibrated meter face that represents a certain amount of power in watts.



(a)



(b)

Fig. 11-24

ELECTRONIC FUNDAMENTALS

EXPERIMENT LESSON 11

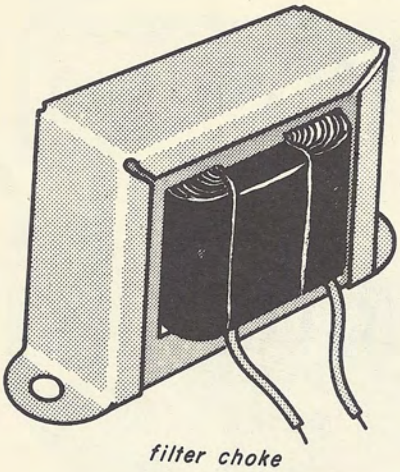
CALCULATION OF METER MULTIPLIERS AND SHUNTS

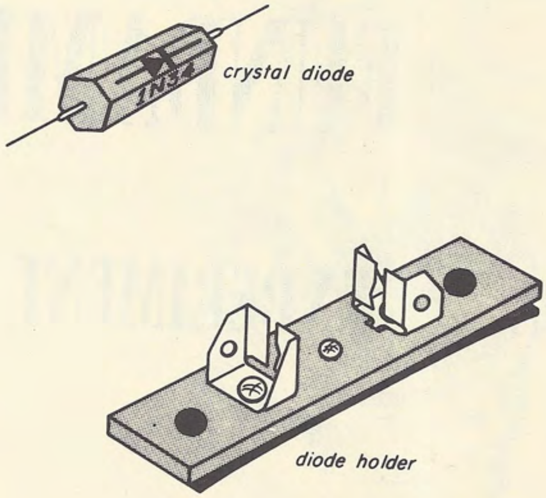
RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA

HOME STUDY SCHOOL

350 West 4th Street, New York 14, N. Y.





All the parts in Kit 6 are listed below. Check the parts you receive against this list. Make sure you have the correct quantity of every item. If a part is either missing or defective upon arrival, request a replacement from Department R, Home Study School, RCA Institutes, Inc., 350 West 4th Street, New York 14, N.Y. *Your request must include your name and student number, the complete name and description of the part copied from the Item column below, the Quantity missing or defective, and the reason you are asking for a new part.*

KIT 6

BILL OF MATERIALS

Quantity	Item
2	Crystal diodes
3	Diode holders
1	Capacitor, 0.01 μf, paper, 1,600 volts, tubular
1	Choke, filter, 400 ohms, 8 h at 50 ma
1	6′ line cord with male plug
2	Resistors, 10 megohms, ½ watt, 10%
5′	#20 solid wire

Experiment Lesson 11

OBJECT

To gain a better understanding of your multimeter by checking the calculations for the voltmeter, ammeter, and ohmmeter sections.

INTRODUCTION

This is an unusual experiment lesson. In it, you will not find experiments of the usual type. Yet, it is one of the most important and valuable lessons in this course. Your multimeter, which you will complete in Experiment Lesson 13, is one of the most important tools you will ever use. It is not enough that you know how to use the meter to make certain measurements; you should know what each part in each meter circuit does and why it was selected.

In Theory Lesson 11, you learned the reasons for placing multipliers and shunts in your multimeter. You learned how to calculate the values of these multipliers and shunts. In the first part of this experiment lesson, you will use this knowledge to calculate the values of the multipliers and shunts used in your multimeter. By doing so, you will gain a better understanding of why these resistors are used in your meter. This understanding will help you to find trouble in your meter circuits.

Note: In making these calculations and others that will come up in the course, it is a good idea to use powers of ten. You remember that we discussed them in Theory Lesson 7. If you haven't been using them, you would do well to get into the habit of doing so. If you need to brush up on the use of powers of ten, reread the part of Theory Lesson 7 that discusses how to use them. Of course, if you find some other method easier or more convenient to use, by all means use it.

If you master this easy-to-learn material, you will never find yourself in the position of the many radio and television servicemen who do not know enough about their meters to locate and repair troubles and who, therefore, must send their meters to a meter repair shop. Such servicemen lose money in two ways. They must miss calls because they do not have a meter and they must pay for the repairs that they could have made themselves if they had known all that you are going to learn about meters in this lesson.

JOB 11-1

To calculate the resistance values of multipliers used in the d-c voltmeter section of your multimeter.

EQUIPMENT NEEDED

Several sheets of unlined paper, 8½ x 11 inches

Pen or pencil

Procedure.

Step 1. Draw a schematic symbol for a meter movement. Mark the inside of the circle 50 μa, and under it write the meter re-

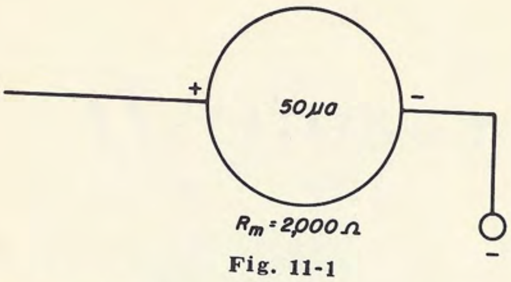


Fig. 11-1

sistance, R_m = 2,000. Draw a line from the negative side of the meter symbol to the negative meter jack. Your drawing should look like Fig. 11-1. Notice that the positive lead of the meter movement is not connected to a positive meter jack. As you calculate multiplier values, you will add resistors in series with this positive lead.

Step 2. Using the formula $E = I_m \times R_m$, calculate the voltage across the terminals of the meter you have drawn. Read no further until you have finished your calculations.

If your calculations are correct, you should have the following result:

$$E = 0.00005 \times 2{,}000$$
$$= 5 \times 10^{-5} \times 2 \times 10^3$$
$$= 10 \times 10^{-2}$$
$$= 0.1 \text{ volt}$$

or

$$E = 0.00005 \times 2.000$$
$$= 0.05 \times 2$$
$$= 0.1 \text{ volt}$$

If your answer does not agree with the value given here, check your calculations to find out where you made a mistake. This is very important. REMEMBER – THE PURPOSE OF DOING THIS WORK IS NOT TO GET THE RIGHT ANSWERS ANY WAY THAT YOU CAN, BUT TO LEARN HOW TO CALCULATE CORRECTLY. The result of your calculations shows that the movement of your meter can be used to measure voltages up to 0.1 volt. (When 0.1 volt is applied to your meter, the meter needle will be deflected full scale.) This is not a very useful limit to the range of your meter, so let us calculate the values of multipliers that will increase its range.

Step 3. Use the following formula in this step:

$$R_t = \frac{E}{I_m}$$

Calculate the total resistance that will be required in the circuit of your meter if you wish to use the meter to measure voltages up to 5 volts d.c. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following result:

$$R_t = \frac{5}{5 \times 10^{-5}}$$
$$= \frac{5 \times 10^5}{5}$$
$$= 10^5$$
$$= 100{,}000 \text{ ohms}$$

or:

$$R_t = \frac{5}{0.00005}$$

$$= 0.00005 \overline{)5.00000} \quad 100{,}000$$

$$= 100{,}000 \text{ ohms}$$

Step 4. To find the value of the multiplier required, subtract the resistance of the meter from R_t. Read no further until you have completed your calculations.

If your calculations are correct, you

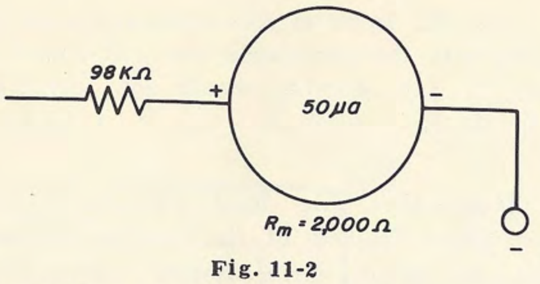


Fig. 11-2

should have the following result:

$$R_s = 100{,}000 - 2{,}000$$
$$= 98{,}000 \text{ ohms}$$

Therefore, the resistance value of the multiplier should be 98,000 ohms. Draw this re-resistor on your schematic diagram, as shown in Fig. 11-2.

Step 5. Calculate the value of the multiplier that must be added to the meter circuit shown in Fig. 11-2 so that the meter can be used to measure voltages up to 25 volts d.c. The procedure is the same as that described in Steps 3 and 4. Read no further until you have performed your calculations.

If your calculations are correct, you should have the following result:

$$R_t = \frac{E}{I_m}$$
$$= \frac{25}{5 \times 10^{-5}}$$
$$= 5 \times 10^5$$
$$= 500{,}000 \text{ ohms}$$

$$R_{25\text{-v mult}} = R_t - (R_m + R_{5\text{-v mult}})$$
$$= 500{,}000 - (2{,}000 + 98{,}000)$$
$$= 500{,}000 - 100{,}000$$
$$= 400{,}000 \text{ ohms}$$

Step 6. Add the multiplier you chose in Step 5 to your schematic drawing. Your drawing should now look like Fig. 11-3.

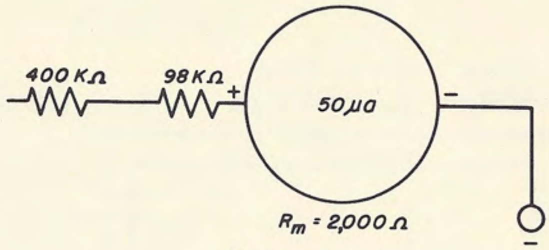


Fig. 11-3

Step 7. Calculate the value of the multiplier required to enable the meter shown in Fig. 11-3 to read 100 volts d.c. Once more, the procedure is the same as that described in Steps 3 and 4. Read no further until you have completed your calculation.

If your calculations are correct, you should have the following results:

$$R_t = \frac{E}{I_m}$$
$$= \frac{100}{5 \times 10^{-5}}$$
$$= \frac{100 \times 10^5}{5}$$
$$= \frac{10 \times 10^6}{5}$$
$$= 2 \times 10^6$$
$$= 2 \text{ megohms}$$

$$R_{100\text{-v mult}} = R_t - (R_m + R_{5\text{-volt mult}} + R_{25\text{-v mult}})$$
$$= 2{,}000{,}000 - (2{,}000 + 98{,}000 + 400{,}000)$$
$$= 2{,}000{,}000 - 500{,}000$$
$$= 1{,}500{,}000 \text{ ohms}$$

Step 8. Draw on your schematic a multiplier with the resistance value you calculated in Step 7. Your drawing should now

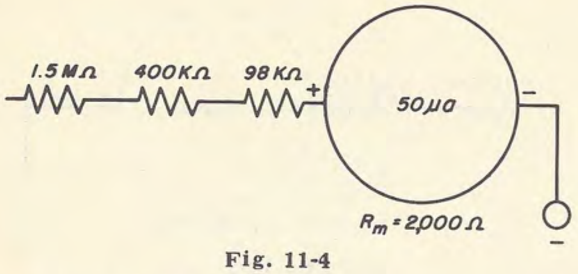


Fig. 11-4

look like Fig. 11-4.

Step 9. Calculate the value of resistance of a multiplier that will enable your multimeter to measure voltages up to 500 volts d.c. Use the same procedure you have used to calculate the other multipliers in your meter. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$R_t = \frac{E}{I_m}$$

$$= \frac{500}{5 \times 10^{-5}}$$

$$= \frac{500 \times 10^5}{5} = \frac{5 \times 10^7}{5}$$

$$= 10^7$$

$$= 10 \text{ megohms}$$

$$R_{500\text{-v mult}} = R_t - (R_m + R_{100\text{-v mult}} + R_{25\text{-v mult}} + R_{5\text{-v mult}})$$

$$= 10{,}000{,}000 - (2{,}000 + 1{,}500{,}000 + 400{,}000 + 98{,}000)$$

$$= 10{,}000{,}000 - 2{,}000{,}000$$

$$= 8{,}000{,}000 \text{ ohms}$$

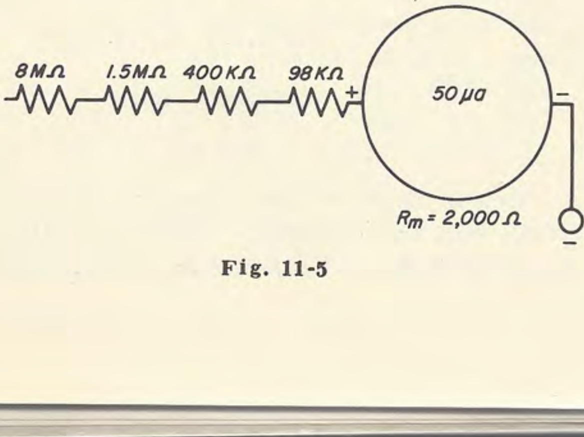


Fig. 11-5

Step 10. Draw on your schematic a multiplier with the resistance you calculated in Step 7. Your drawing should now look like Fig. 11-5.

Discussion. You have calculated the resistance values of the multipliers that are used in your meter. If you compare Fig. 11-5 with the schematic diagram of your multimeter shown in Fig. 11-6, you will see that the total resistance value of the multipliers used in both circuits is the same However, you will note one difference; the circuit shown in Fig. 11-6 uses two resistors for the 98 k-ohm multiplier. The 98 k-ohm multiplier is so divided because of certain features of the ammeter section, which will be discussed later in this lesson.

Figure 11-6 shows the switch used to connect multipliers into the meter circuit. Another way of showing this switch (actually a simplified way of showing it) can be seen in Fig. 11-7. In the figure, the switch is in a position that connects the 98 k-ohm, 400 k-ohm, and 1.5-megohm multipliers into the circuit. With these multipliers in the circuit, the voltmeter section of your multimeter is set to the 100 VDC range. Moving the switch arm to the right cuts out multipliers and lowers the voltage range. For example, if the switch arm were moved so that it was between the 1.5 megohm multiplier and the 400-k ohm multiplier, the 1.5-megohm multiplier would be out of the voltmeter circuit and the switch would be in the 25 VDC position. Moving the switch to the left would add the 8-megohm multiplier to the circuit and, therefore, the switch would be in the 500 VDC position.

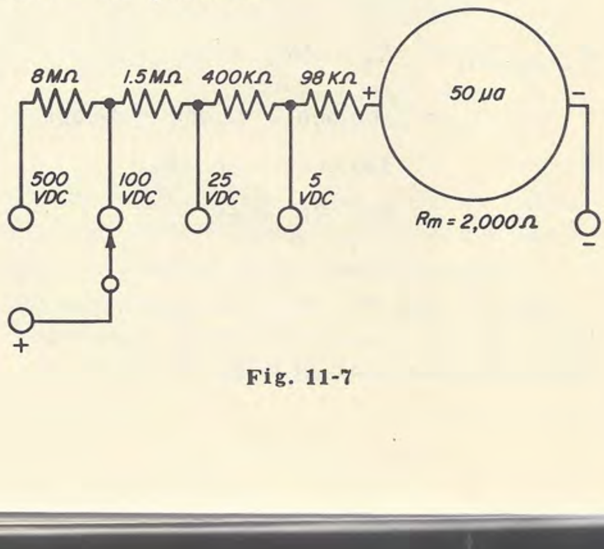


Fig. 11-7

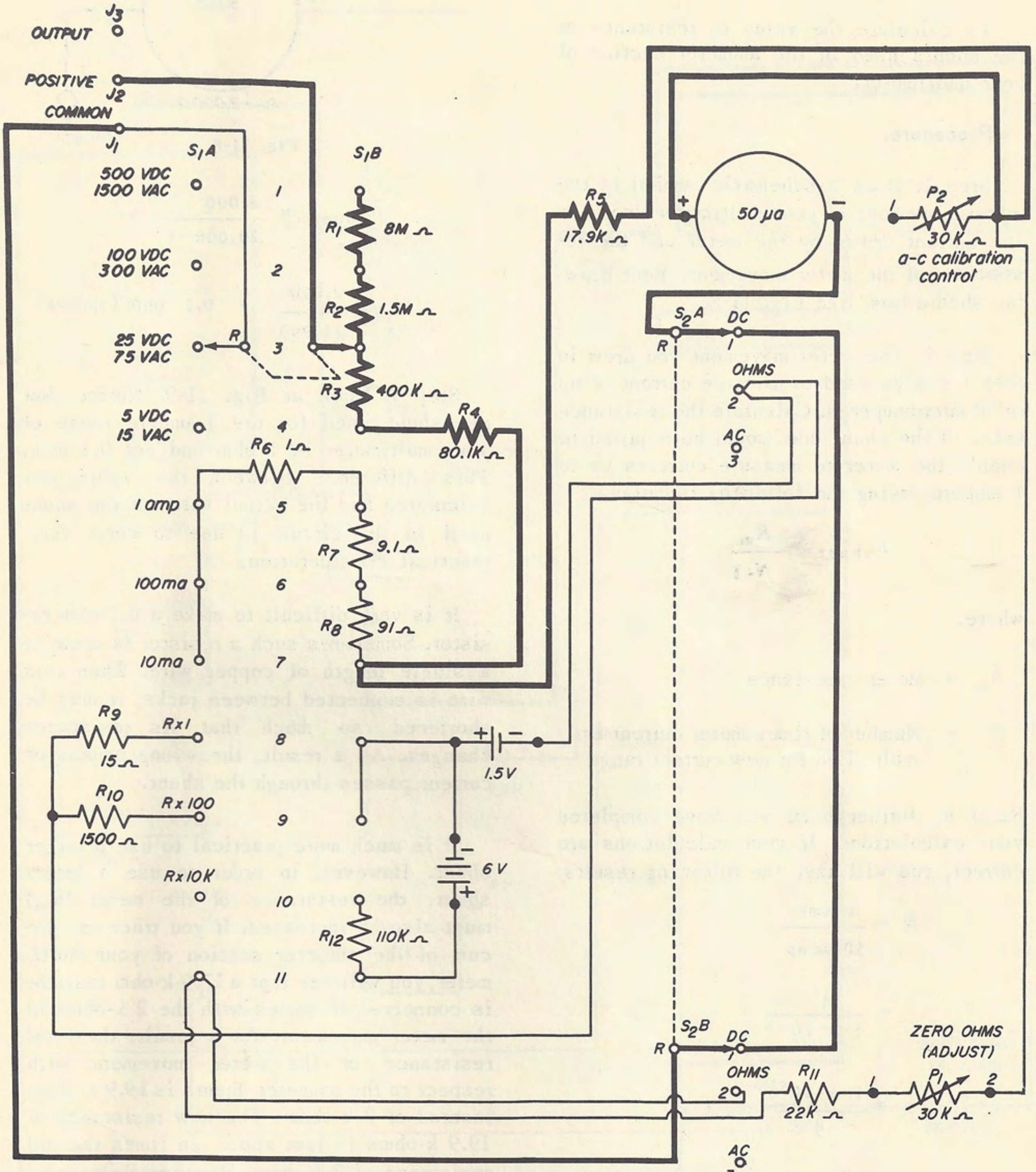

OUTPUT
J_3
POSITIVE
J_2
COMMON
J_1
S_1A
S_1B
500 VDC
1500 VAC
1
R_1
8M Ω
100 VDC
300 VAC
2
R_2
1.5M Ω
25 VDC
75 VAC
R
3
R_3
400K Ω
5 VDC
15 VAC
4
R_4
80.1K Ω
R_6
1 Ω
1 amp
5
R_7
9.1 Ω
100ma
6
R_8
91 Ω
10ma
7
R_9
Rx1
15 Ω
8
1.5V
R_{10}
Rx100
1500 Ω
9
6V
Rx10K
10
R_{12}
110K Ω
11
R_5
17.9K Ω
50 μa
P_2
30 K Ω
a-c calibration
control
S_2A
R
DC
1
OHMS
2
AC
3
S_2B
ZERO OHMS
(ADJUST)
R_{11}
22K Ω
P_1
30 K Ω

Fig. 11-6

JOB 11-2

To calculate the value of resistance of the shunts used in the ammeter section of your multimeter.

Procedure.

Step 1. Draw a schematic symbol of the meter movement of your multimeter. Indicate the current drawn by the meter and the resistance of the meter movement. Your drawing should look like Fig. 11-8.

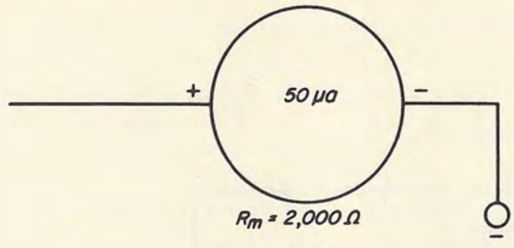


Fig. 11-8

Step 2. The meter movement you drew in Step 1 can be used to measure current of up to 50 microamperes. Calculate the resistance value of the shunt that would be required to enable the meter to measure currents up to 1 ampere, using the following formula:

$$R_{shunt} = \frac{R_m}{N-1}$$

where:

R_m = Meter resistance

N = Number of times meter current is multiplied for new current range

Read no further until you have completed your calculations. If your calculations are correct, you will have the following results:

$$N = \frac{1 \text{ amp}}{50\ \mu\text{amp}}$$

$$= \frac{1}{5 \times 10^{-5}}$$

$$= \frac{1 \times 10^5}{5}$$

$$= \frac{10 \times 10^4}{5}$$

$$= 2 \times 10^4$$

$$= \cdot 20{,}000$$

$$R_{shunt} = \frac{2{,}000}{20{,}000-1}$$

$$= \frac{2{,}000}{19{,}999} = 0.1 \text{ ohm (approx)}$$

Step 3. Look at Fig. 11-9. Notice that the shunt used for the 1-ampere range of your multimeter is 1 ohm and not 0.1 ohm. This difference between the value you calculated and the actual value of the shunt used in the circuit is due to some very practical considerations.

It is very difficult to make a 0.1-ohm resistor. Sometimes such a resistor is made of a single length of copper wire. When this wire is connected between jacks, it may be shortened so much that its resistance changes. As a result, the wrong amount of current passes through the shunt.

It is much more practical to use a larger shunt. However, in order to use a larger shunt, the resistance of the meter (R_m) must also be increased. If you trace the circuit of the ammeter section of your multimeter, you will see that a 17.9-k-ohm resistor is connected in series with the 2 k-ohms of the meter movement. As a result, the total resistance of the meter movement with respect to the ammeter shunts is 19.9 k-ohms instead of 2 k-ohms. The new resistance of 19.9 k-ohms is just about ten times the old resistance of 2 k-ohms. Because R_7 and R_8 are small, they are neglected in our calculations for the sake of simplicity. Therefore, it is possible to use shunts that have a resistance value ten times greater than that of the shunts that can be used with a 2 k-ohm movement.

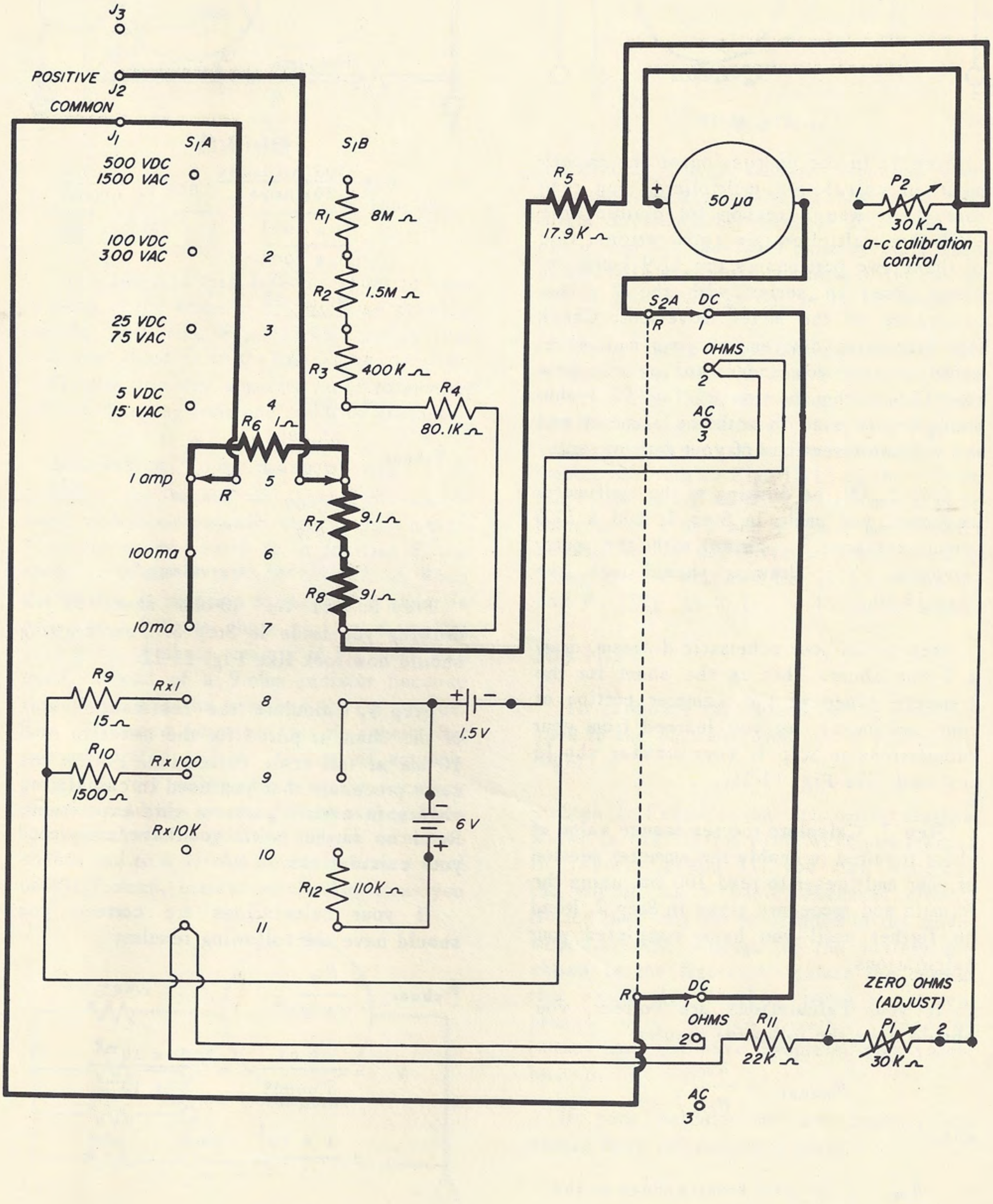

J3
POSITIVE
J2
COMMON
J1
S1A
S1B
500 VDC
1500 VAC
100 VDC
300 VAC
25 VDC
75 VAC
5 VDC
15 VAC
1
2
3
4
5
6
7
8
9
10
11
R1
8M Ω
R2
1.5M Ω
R3
400K Ω
R4
80.1K Ω
R6
1 Ω
1 amp
R
100ma
10ma
R7
9.1 Ω
R8
91 Ω
R9
15 Ω
Rx1
R10
1500 Ω
Rx100
Rx10K
1.5V
6V
R12
110K Ω
R5
17.9K Ω
50 μa
P2
30K Ω
a-c calibration control
S2A
DC
OHMS
AC
ZERO OHMS (ADJUST)
R11
22K Ω
P1
30K Ω

Fig. 11-9

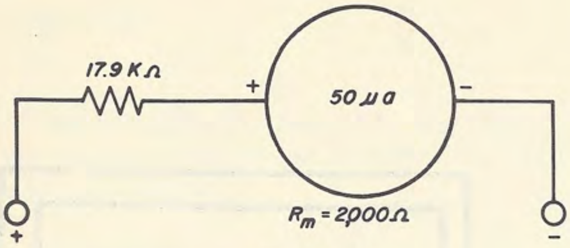


Fig. 11-10

Step 4. In the discussion of the experiment in calculating multipliers, you read that there was a reason for dividing the 98 k-ohm multiplier into two portions. One of these two portions is the 17.9 k-ohm resistor used in series with the 2 k-ohm resistance of the meter movement. Check the schematic diagram of your multimeter again so that you understand exactly how the 17.9 k-ohm portion of the 98 k-ohm multiplier is used in both the ammeter and the voltmeter sections of your multimeter.

Step 5. On the drawing of the multimeter movement you made in Step 1, add a 17.9 k-ohm resistor in series with the meter movement. Your drawing should look like Fig. 11-10.

Step 6. On your schematic diagram, draw a 1-ohm shunt. This is the shunt for the 1-ampere range of the ammeter portion of your multimeter, as you learned from your calculations in Step 1. Your drawing should now look like Fig. 11-11.

Step 7. Calculate the resistance value of shunt required to enable the ammeter section of your multimeter to read 100 ma, using the formula and procedure given in Step 2. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$R_{shunt} = \frac{R_m}{N-1}$$

where:

R_m = 17.9 k-ohms added to the resistance of the meter movement.

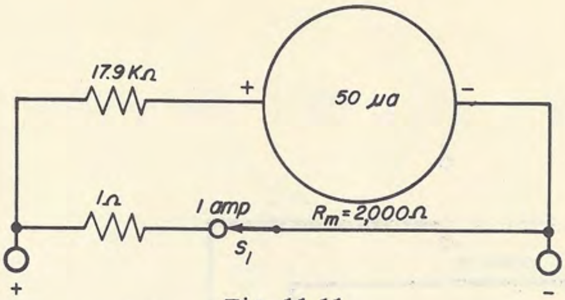


Fig. 11-11

$$N = \frac{100 \text{ milliamps}}{50\ \mu\text{amps}} = \frac{0.1}{0.00005}$$

$$= \frac{1 \times 10^{-1}}{5 \times 10^{-5}} = \frac{1 \times 10^{4}}{5}$$

$$= \frac{10 \times 10^{3}}{5}$$

$$= 2 \times 10^{3}$$

$$= 2000$$

$$R_{shunt} = \frac{19{,}900}{2000 - 1}$$

$$= \frac{19{,}900}{1{,}999}$$

$$= 10 \text{ ohms (approximately)}$$

Step 8. Add the 10-ohm shunt to the drawing you made in Step 5. Your drawing should now look like Fig. 11-12.

Step 9. Calculate the resistance value of the shunt required for the meter to read 10 ma at full-scale deflection. Follow the same procedure that you used in calculating shunts in earlier parts of this experiment. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$R_{shunt} = \frac{R_m}{N-1}$$

$$N = \frac{0.01}{0.00005} = \frac{1 \times 10^{-2}}{5 \times 10^{-5}}$$

$$= \frac{1 \times 10^{3}}{5}$$

$$= 2 \times 10^{2}$$

$$= 200$$

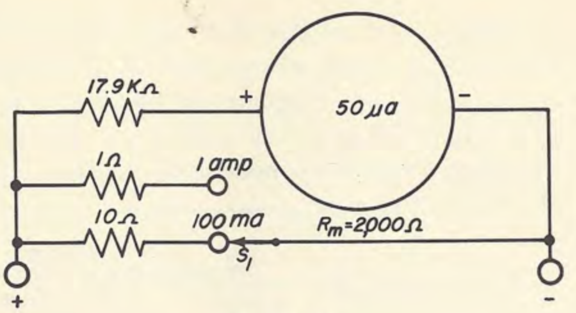


Fig. 11-12

$$R_{\text{shunt}} = \frac{19{,}900}{200 - 1} = \frac{19{,}900}{199} = 100 \text{ ohms}$$

Step 10. Add this 100-ohm shunt to your drawing of the ammeter circuit. Your drawing should look like Fig. 11-13. Notice that only one shunt is in the circuit at one time. Switching from one ammeter range to another means changing from one shunt to another.

Discussion. Look again at Fig. 11-9. Compare the values of shunts you calculated with those actually used in your meter. When the range switch is in position 5, the shunt is 1 ohm — as you calculated. When the switch is position 6, the 1-ohm shunt is added to a 9.1-ohm shunt, making a total of 10.1 ohms. A shunt resistor of 9.1 ohms was used instead of a 9-ohm resistor because this value was the standard RETMA value. The difference between the 10 ohms that you calculated and the 10.1 ohms actually used has very slight effect on the accuracy of your readings on the 100-ma range. When the switch is in position 7, the first two shunts add to a 91-ohm shunt, making a total of 101.1 ohms, instead of the 100 ohms you

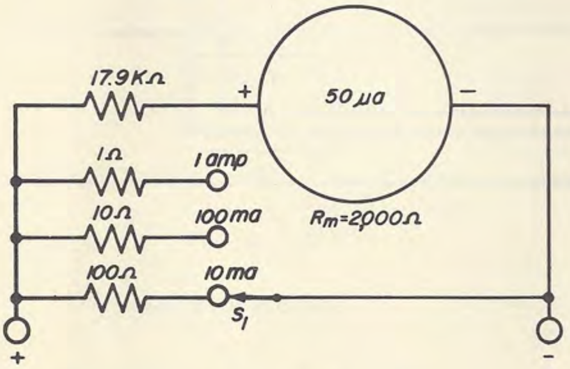


Fig. 11-13

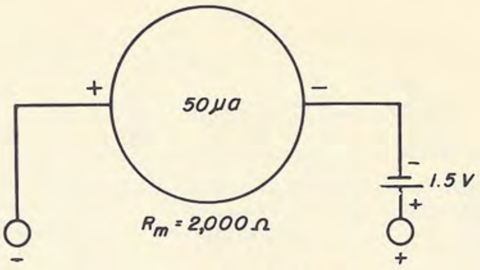


Fig. 11-14

calculated. The 91-ohm resistor was used because it is a standard RETMA value. The slight difference between the 100 ohms you calculated and the 101.1 ohms actually used makes only a slight difference in the accuracy of your readings on the 10-ma range.

Thus, the values calculated with the simple shunt formula can be translated to those of the Universal shunt formula. This can be done by subtracting any simple shunt value from the next higher value. For example, referring to Fig. 11-13 on the 100-ma range, the shunt should be 10 ohms; this is made up of 1 ohm and 9 ohms, which would be obtained by the Universal shunt formula. Thus, the 10-ohm resistor becomes the R_6 and R_7 (Fig. 11-9) in the Universal shunt.

JOB 11-3

To calculate the values of the resistors used in the ohmmeter section of your multimeter.

Step 1. Examine the schematic diagram shown in Fig. 11-14. From what you learned in Theory Lesson 11, you may recognize the circuit as a basic ohmmeter circuit. Notice that only the resistance of the movement and the voltage of the battery are shown in the figure. Calculate the current that would flow in this circuit if the test probes were shorted together. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following result:

$$I = \frac{1.5}{2 \times 10^3} = 0.75 \times 10^{-3}$$

$$= 0.00075 = 750\ \mu\text{amps}$$

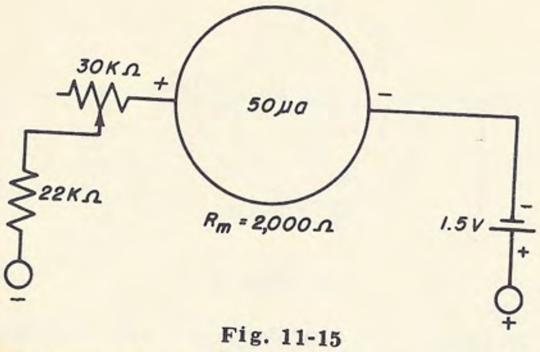


Fig. 11-15

Step 2. You know that the movement of your meter is rated at 50 microamperes. To limit the current flowing in the circuit to that value, a 22 k-ohm resistor and a 30 k-ohm rheostat have been inserted in the circuit, as shown in Fig. 11-15. To understand the function of these resistors, calculate the amount of resistance that is required in the circuit if the 1.5-volt cell is to produce a current flow of 50 μamps in the circuit. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results: .001 = 1 MA

$$R = \frac{1.5}{50 \times 10^{-6}} \qquad \frac{9}{\cancel{100} \times 10^{-3}}$$

$$= \frac{1.5 \times 10^6}{50} \qquad \frac{9 \times 10^3}{100}$$

$$= \frac{150 \times 10^4}{50} \qquad \cancel{\frac{900 \times 10^4}{100}}$$

$$= 3 \times 10^4 \qquad 9 \times 10^3$$

$$= 30{,}000 \text{ ohms} \qquad 90{,}000$$

The resistance of the meter is 2,000 ohms. The resistance of the 22 k-ohm resistor added to the resistance of the meter gives a total of 24 k-ohms. According to your calculations, only 6 k-ohms more are required to maintain current at the proper level. The 30 k-ohm variable resistor (a potentiometer connected as a rheostat) will provide this 6 k-ohm resistance, or more resistance, or less resistance.

Step 3. Let us find out why a 30 k-ohm rheostat is used where one of 6 k-ohms seems sufficient. Suppose the voltage of the 1.5-volt cell should drop as low as 1.2 volts. Then the resistance necessary to limit the current to 50 μa is:

$$R_s = \frac{1.2}{0.00005} \qquad \frac{7}{100\cancel{X}}$$

$$= \frac{1.2}{5 \times 10^{-5}} \qquad \frac{7}{10^{-3}}$$

$$= \frac{1.2 \times 10^5}{5} \qquad 7 \times 10^3$$

$$= \frac{12 \times 10^4}{5}$$

$$= 2.4 \times 10^4$$

$$= 24{,}000 \text{ ohms} \qquad 70{,}000$$

A series resistance of 22,000 ohms added to the 2,000 ohms of the meter movement is the smallest value that we are likely to need.

Step 4. Now let us calculate the greatest value of resistance we are likely to need. Look at Fig. 11-16. It shows the ohmmeter section of your multimeter. When the range switch is in the $R \times 10K$ position, there is a total of 7.5 volts used in the ohmmeter circuit. The series resistance necessary to limit the current to 50 μa is:

$$R_s = \frac{7.5}{0.00005} \qquad \frac{10}{.0001}$$

$$= \frac{7.5}{5 \times 10^{-5}}$$

$$= \frac{7.5 \times 10^5}{5}$$

$$= 1.5 \times 10^5$$

$$= 150{,}000 \text{ ohms}$$

In series with the battery voltage we have R_{12} (110 k-ohms), R_{11} (22 k-ohms), and

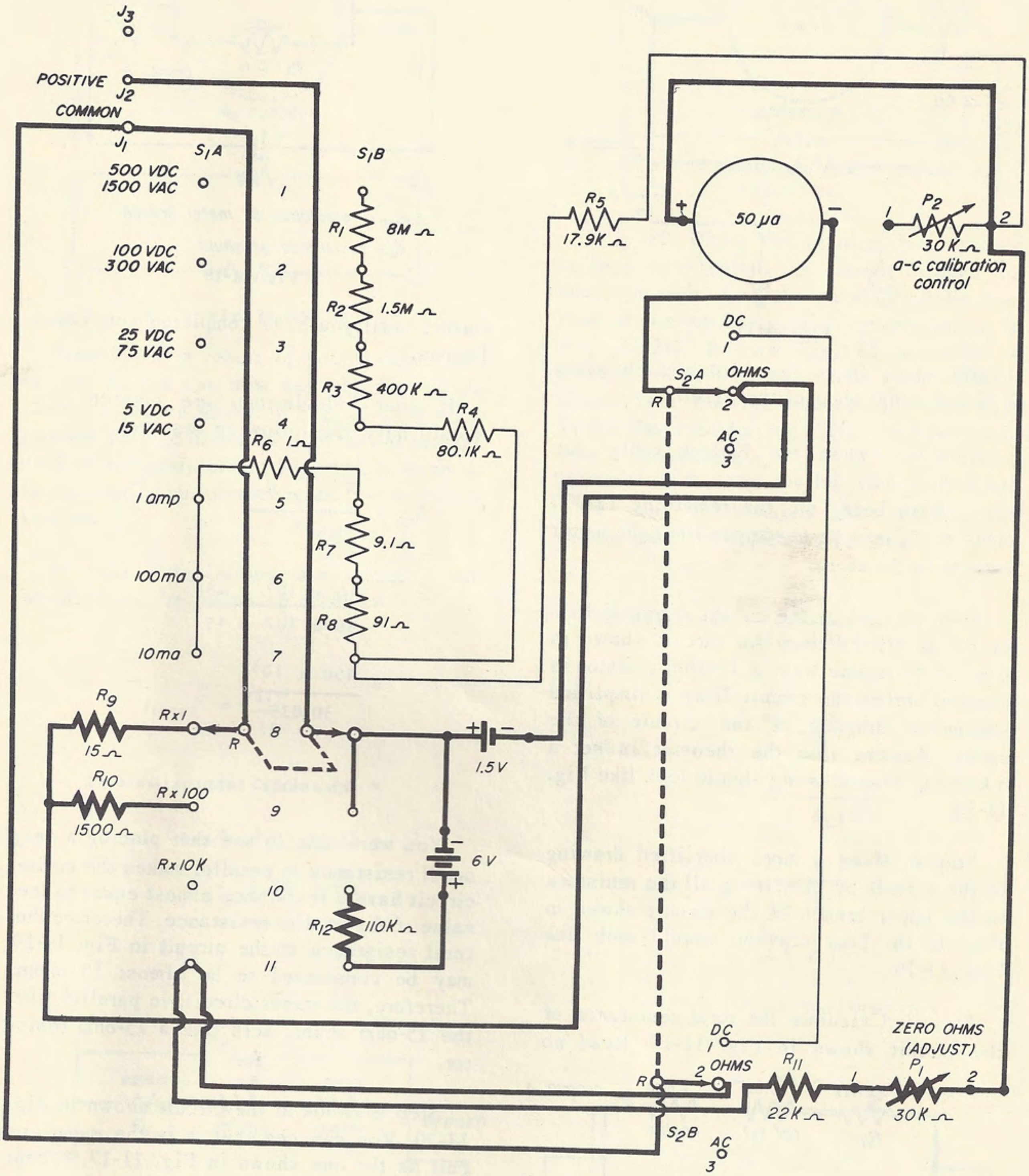

J3
POSITIVE
J2
COMMON
J1
S1A
S1B
500 VDC
1500 VAC
1
R1
8M Ω
100 VDC
300 VAC
2
R2
1.5M Ω
25 VDC
75 VAC
3
R3
400 K Ω
R4
80.1K Ω
5 VDC
15 VAC
4
R6
1 Ω
1 amp
5
R7
9.1 Ω
100 ma
6
R8
91 Ω
10 ma
7
R9
15 Ω
Rx1
R
8
1.5V
R10
1500 Ω
Rx 100
9
6V
Rx10K
10
R12
110K Ω
11
R5
17.9K Ω
50 μa
1
P2
2
30 K Ω
a-c calibration
control
DC
1
S2A
OHMS
R
2
AC
3
DC
1
OHMS
2
R
R11
22K Ω
ZERO OHMS
(ADJUST)
P1
1
2
30K Ω
S2B
AC
3

Fig. 11-16

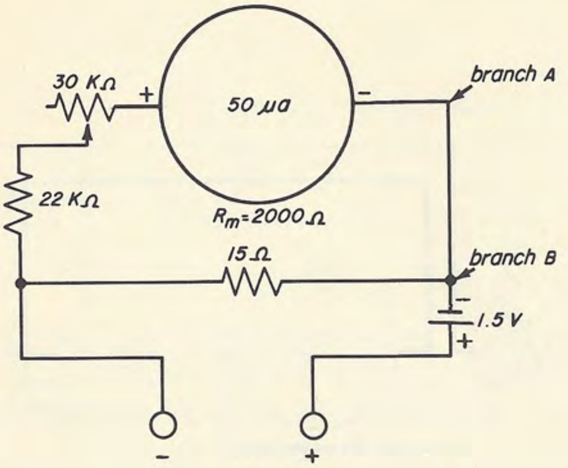


Fig. 11-17

16,000 ohms (from the 30 k-ohm rheostat, P_1), and 2,000 ohms of the meter.

However, when the battery cells are fresh they may deliver more than 1.5 volts each. This being so, the remaining 12,000 ohms of P_1 may be needed to limit the meter current to 50 ua.

Step 5. Look at the circuit shown in Fig. 11-17. It differs from the circuit shown in Fig. 11-15 in one way; a 15-ohm resistor is shunted across the circuit. Draw a simplified schematic diagram of the circuit of the meter. Assume that the rheostat is set a 6 k-ohms. Your drawing should look like Fig. 11-18.

Step 6. Make a more simplified drawing of the circuit by combining all the resistors in the upper branch of the circuit shown in Fig. 11-18. Your drawing should look like Fig. 11-19.

Step 7. Calculate the total resistance of the circuit shown in Fig. 11-19. Read no

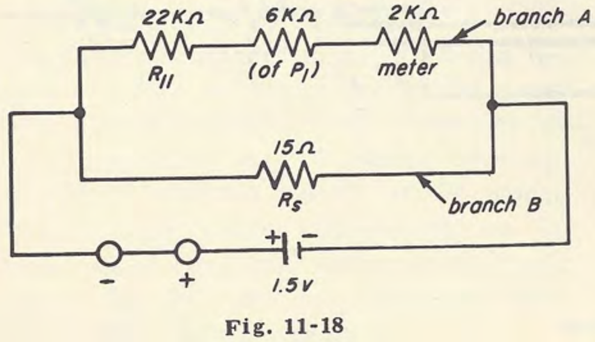
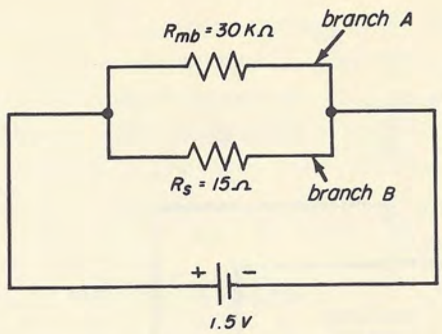


Fig. 11-18



R_{mb} = resistance of meter branch

R_s = resistance of shunt

Fig. 11-19

further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$R_t = \frac{R_{mb} \times R_s}{R_{mb} + R_s}$$

$$= \frac{30 \times 10^3 \times 15}{30 \times 10^3 + 15}$$

$$= \frac{450 \times 10^3}{30{,}015}$$

$$= 15 \text{ ohms (approximately)}$$

You were able to see that placing a very small resistance in parallel makes the entire circuit have a resistance almost equal to the value of the smaller resistance. Therefore the total resistance of the circuit in Fig. 11-19 may be considered to be almost 15 ohms. Therefore, the meter circuit, in parallel with the 15-ohm shunt, acts like a 15-ohm resistor.

Step 8. Look at the circuit shown in Fig. 11-20. You can see that it is the same circuit as the one shown in Fig. 11-17, except that a 15-ohm resistor is connected across terminals *A* and *B* of the meter. Draw a simplified circuit of the meter circuit shown in Fig. 11-20. Assume that the 30 k-ohm rheostat is set at 6 k-ohms. Your drawing should look like Fig. 11-21.

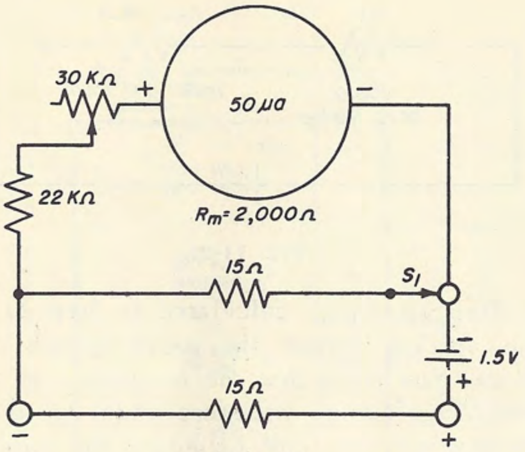


Fig. 11-20

Step 9. As a result of your calculations in Step 6, you can now see why Fig. 11-21 can be drawn as shown in Fig. 11-22. Calculate the voltage drops and the current through each of the resistors in Fig. 11-22. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$I_{\text{total}} = \frac{1.5}{30}$$

$$= 0.05 \text{ amps}$$

$$E_{\text{Rmc}} = 0.05 \times 15$$

$$= 0.75 \text{ volts}$$

$$E_{\text{Rx}} = 0.05 \times 15$$

$$= 0.75 \text{ volts}$$

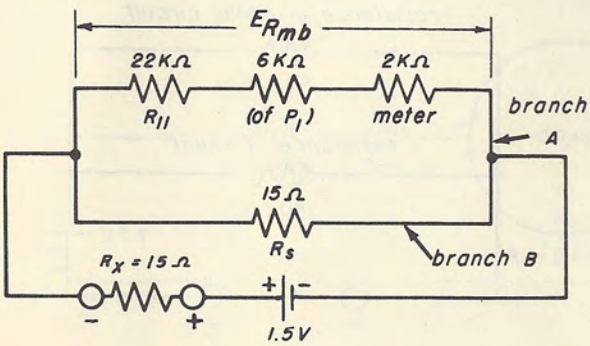
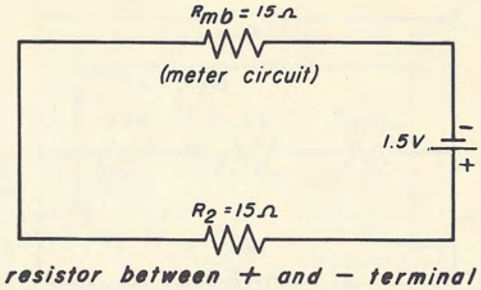


Fig. 11-21



resistor between + and − terminal
Fig. 11-22

Step 10. Using the results you obtained in Step 9, calculate the current through the meter (branch A of the parallel circuit portion of the series-parallel circuit shown in Fig. 11-21). Redraw Fig. 11-21 so as to make it easier for you to make your calculations. Your drawing should look like Fig. 11-23. Read no further until you have made your calculations.

If your calculations are correct, you should have the following results:

$$I_{\text{Branch A}} = \frac{0.75}{30 \times 10^3}$$

$$= \frac{0.75 \times 10^{-3}}{30}$$

$$= \frac{7.5 \times 10^{-4}}{3 \times 10^1}$$

$$= \frac{7.5 \times 10^{-5}}{3}$$

$$= 2.5 \times 10^{-5}$$

$$= 25 \text{ microamperes}$$

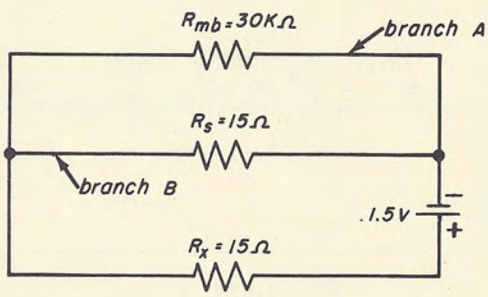


Fig. 11-23

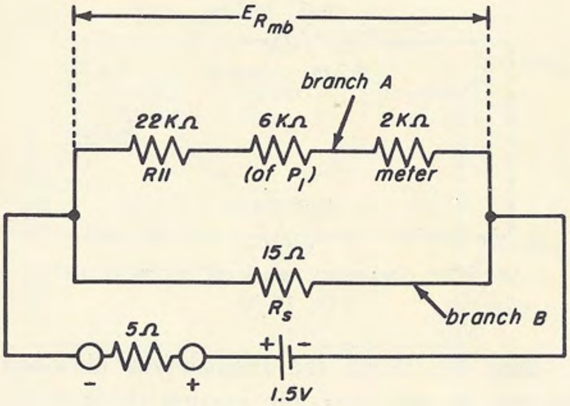


Fig. 11-24

The current going through Branch A is the current that goes through your meter circuit when your meter is connected with the 15-ohm shunt across it and the test leads are applied to a 15-ohm resistor. So, when the needle is in the 25-μa position, it also points to the 15-ohm calibration on the ohms scale.

Step 11. Let us calculate what would happen if the test prods of the meter were connected across a 5-ohm resistor instead of across a 15-ohm resistor, as shown in Fig. 11-24. Figure 11-25 shows the simplified circuit. Using the same method as in Step 9, calculate the voltage across the meter branch and shunt, and the current flowing through the meter. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$I_{total} = \frac{1.5}{20}$$

$$= 0.075 \text{ amp}$$

$$E_{Rmc} = I \times R$$

$$= 0.075 \times 15$$

$$= 1.125 \text{ volts}$$

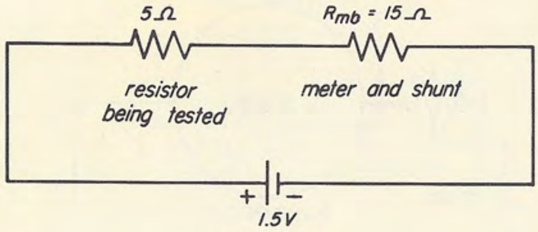


Fig. 11-25

Step 12. E_{Rmc} calculated in Step 11 is the voltage across the meter branch and shunt. You know that the resistance of the meter and series resistors adds up to 30 k-ohms, so you can calculate the current flowing through the meter. Read no further until you have completed your calculations.

If your calculations are correct, you should have the following results:

$$I_{meter} = \frac{1.125}{3 \times 10^4}$$

$$= \frac{1.125 \times 10^{-4}}{3}$$

$$= 0.0000375$$

$$= 37.5 \ \mu\text{amps}$$

The ohmmeter circuit discussed so far uses a 15-ohm shunt resistor. With this shunt resistor in the circuit of your multimeter, the range switch is in the Rx1 position. As you learned in Service Practices 7, the most accurate resistance readings are obtained when the resistance being measured

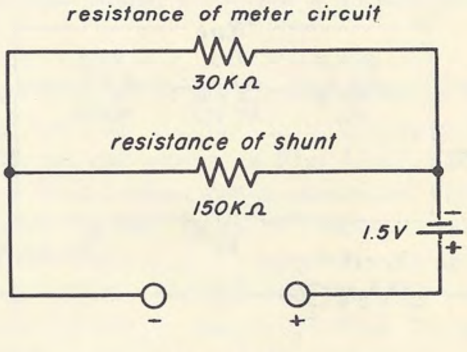


Fig. 11-26

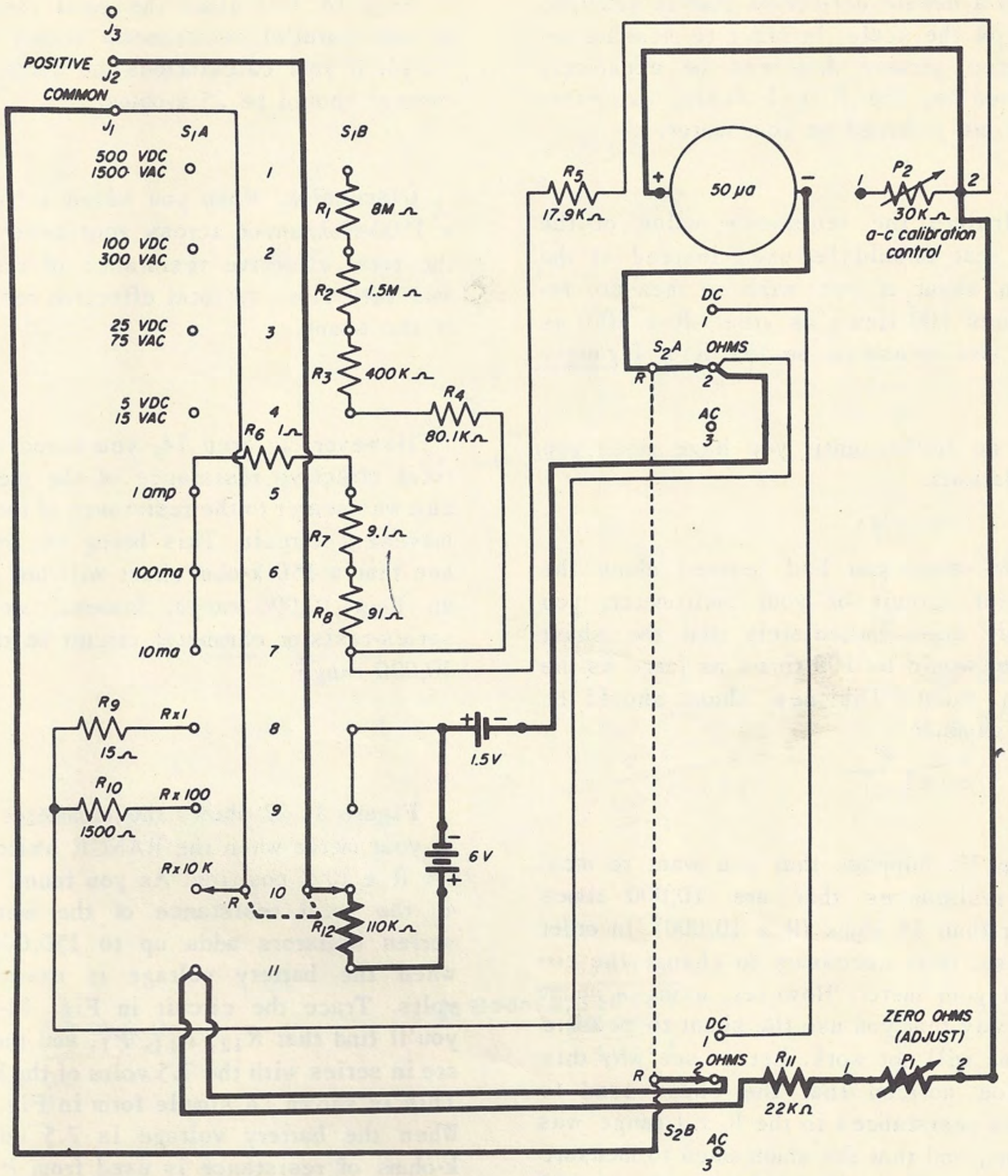


Fig. 11-27

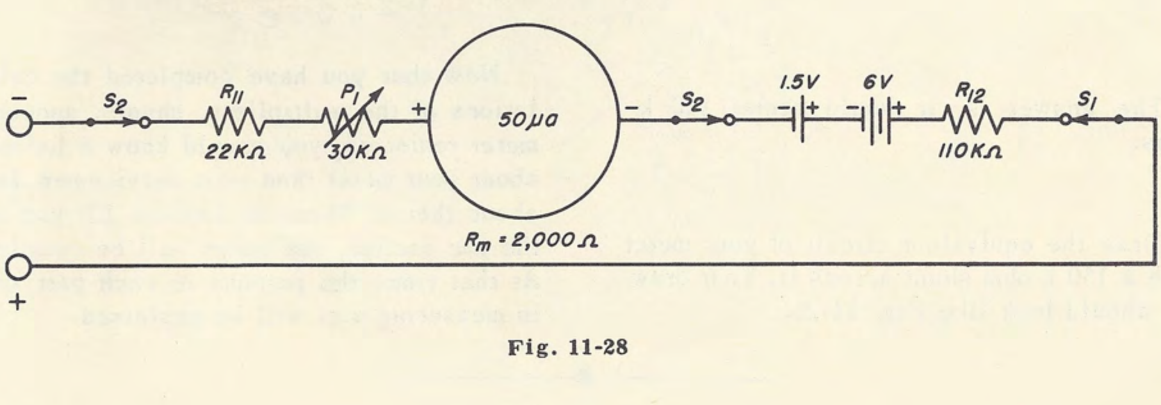


Fig. 11-28

causes a needle deflection that is near the center of the scale. In order to measure resistances greater than can be accurately measured on the R x 1 scale, two other scales are provided on your meter.

Calculate the resistance value of the shunt that should be used instead of the 15-ohm shunt if you wish to measure resistances 100 times as great (R x 100) as those you measured on the R x 1 range.

Read no further until you have made your calculations.

From what you had learned about the ohmmeter circuit of your multimeter, you probably knew immediately that the shunt required would be 100 times as large as the 15-ohm shunt. The new shunt should be 1,500 ohms.

Step 13. Suppose that you want to measure resistances that are 10,000 times greater than 15 ohms (R x 10,000). In order to do so, it is necessary to change the circuit of your meter. However, using a shunt in the way that you use the shunt to measure 15 ohms will not work. Let us see why this so. You noticed that the shunt used to measure resistances in the R x 1 range was 15 ohms, and that the shunt used to measure resistances in the R x 100 range was 1,500 ohms. Calculate the shunt required to measure 150 k-ohms.

The answer is, it would seem, 150 k-ohms.

Draw the equivalent circuit of your meter with a 150 k-ohm shunt across it. Your drawing should look like Fig. 11-26.

Step 14. Calculate the total resistance of the parallel resistances shown in Fig. 11-26. If your calculations are correct, your answer should be 25 k-ohms.

Discussion. When you added a 15-ohm or a 1500-ohm shunt across your meter circuit the total effective resistance of the meter was very close to total effective resistance of the shunt.

However, in Step 14, you found that the total effective resistance of the meter circuit was nearer to the resistance of the meter-movement circuit. This being so, you can see that a 150 k-ohm shunt will not give us an R x 10,000 range. Instead, we use a series-resistor ohmmeter circuit in the R x 10,000 range.

Figure 11-27 shows the ohmmeter circuit of your meter when the RANGE switch is in the R x 10 K position. As you found in Step 4, the total resistance of the meter and series resistors adds up to 150,000 ohms when the battery voltage is exactly 7.5 volts. Trace the circuit in Fig. 11-27 and you'll find that R_{12}, R_{11}, P_1, and the meter are in series with the 7.5 volts of the battery. This is shown in simple form in Fig. 11-28. When the battery voltage is 7.5 volts, 16 k-ohms of resistance is used from P_1, and, as the voltage drops down, an even smaller amount of resistance will be needed to limit the meter current to 50 μa.

Now that you have completed the calculations of the multipliers, shunts, and ohmmeter resistors, you should know a lot more about your meter than most servicemen know about theirs. When, in Lesson 12 you add the a-c portion, the meter will be complete. At that time, the purpose of each part used in measuring a.c. will be explained.

ELECTRONIC FUNDAMENTALS

THEORY LESSON 12

D-C AND A-C GENERATORS

12-1. Direction of Current Flow
12-2. Induced EMF and Current Flow
12-3. Electromagnetic Induction
12-4. Graphs
12-5. Simple A-C Generator
12-6. D-C Generators
12-7. Practical Generators
12-8. Transformers
12-9. Transformer Losses
12-10. Transformer Types

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Theory Lesson 12

INTRODUCTION

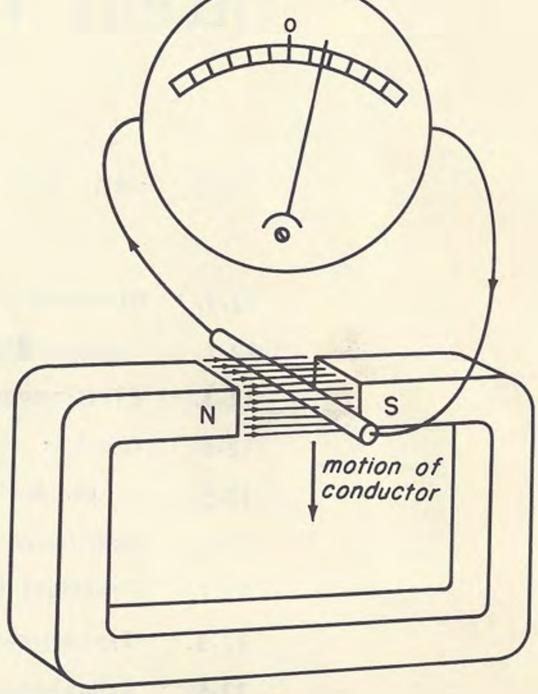
From earlier lessons, you know that electricity can be produced by friction. You know that, by means of friction, electrons may be wiped off a material, leaving it positively charged. The body to which the electrons attach themselves then becomes negatively charged. You know that if these two charged bodies are joined by a conductor, current electricity will flow. You also know that this is not a very satisfactory or practical method of producing electricity. You know, too, that electricity may be produced chemically, as in a primary or secondary cell, and that this method of producing electric power is widely used. However, most of the electricity produced for lighting, heating, cooking, operating motors, radios, TV sets, and so forth, is produced by still another method. We call this the electromagnetic method.

In 1831, an English scientist, Michael Faraday, discovered a strange thing. He found that he could produce an electric current in a closed circuit simply by moving the circuit across a magnetic field or by moving a magnet (and magnetic field) across the circuit. Figure 12-1 shows how this may be done. Part *a* shows a single conductor, connected to a sensitive meter, being moved so that it cuts across the lines of force of a magnet. The meter shown is one with the zero calibration line in the center of the scale, so that the direction of the induced current may be indicated. Part *b* of the figure shows another conductor, one of several turns, connected to a sensitive meter. In this case, the conductor is not moving. Instead, the magnet with its magnetic field is being pushed into the coil.

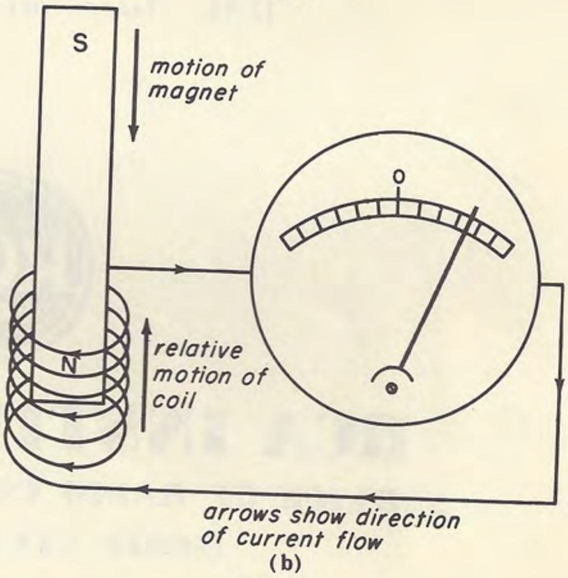
12-1. DIRECTION OF CURRENT FLOW

The direction of the current flow caused by the induced emf is determined by:

1. The direction of flux lines of the magnetic field.



(a)



(b)

Fig. 12-1

2. The direction of the relative motion between the conductor and the magnetic field.

From your study of magnetism, you know that the direction of the flux (magnetic lines of force) is from the North pole, through the field, to the South pole. When we speak of the *relative motion* between the conductor and the magnetic field, we mean that it makes no difference which moves, the conductor or the field, because the effect is the same. So, when the relative motion between the conductor and the magnetic lines of force is reversed, as in Fig. 12-2, the direction of current is opposite to that of the first current. Therefore, the current produced when the magnet is thrust in the coil is opposite to the current produced when the magnet is removed from the coil.

Left-Hand Rule For Generators. There is a rule for finding the direction of current flow. We call it the left-hand rule for generators. It goes like this: Hold the thumb, middle finger, and forefinger of your left hand as shown in Fig. 12-3*a*. If you place them correctly, each finger will be at right angles to the other two. Now, with the fingers still in this position, place your hand over the drawing of Fig. 12-3*b*. Let your thumb point in the direction of motion of the conductor, and your forefinger point in the direction of the flux lines. Your middle finger will point to the direction of the induced emf; that is the direction in which current flows. Please remember that, in these lessons, current flows in the direction of the movement of electrons. If you do this correctly, you will find that the current flows toward you, as shown by the dot in the drawing.

12-2. INDUCED EMF AND CURRENT FLOW

Faraday discovered that:

1. A voltage is induced when there is relative motion between the conductor and the magnetic field.

2. A voltage is induced only when the conductor cuts *across* the lines of force, or the lines of force cut *across* the conductor.

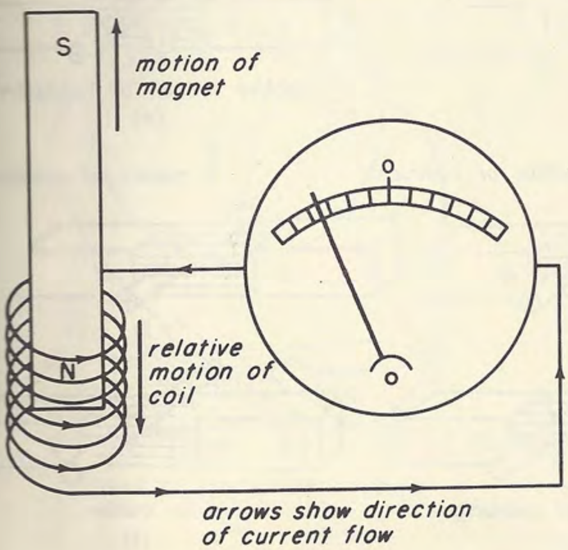
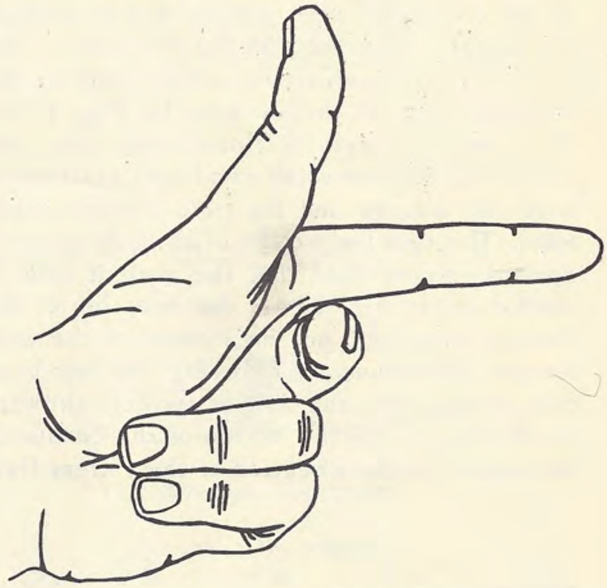
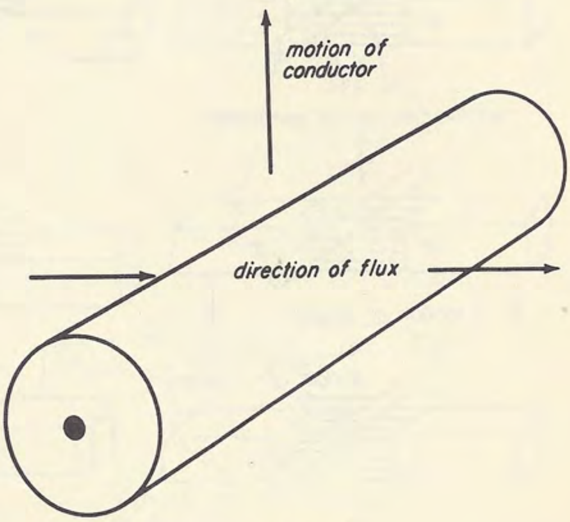


Fig. 12-2



(a)



(b)

Fig. 12-3

3. The polarity of the induced emf reverses when the direction of relative motion between conductor and magnetic field is reversed.

The drawings in Fig. 12-4 show how these facts affect the flow of current in a conductor placed in a magnetic field. Figure 12-4*a* shows the conductor moving downward. By applying our left-hand rule, we see that the direction of current flow is away from us. Figure 12-4*b* shows the motion of the conductor is upward, so that the current now flows toward us. In 12-4*c*, the conductor is stationary and the magnet with its field moves upward. The relative motion between the magnet and the conductor is, therefore, the same as it would be if the conductor were moving downward with the magnet stationary. So the direction of the relative motion, which we use in applying the left-hand rule, is the same as for Fig. 12-4*a*. Therefore the current flows away from us. Figure 12-4d shows the conductor stationary, with the magnet and its field moving downward. The relative motion of the conductor is upward, so we find that the current flow is toward us. In Fig. 12-4*e*, the direction of the flux is reversed, so the motion of the conductor is downward. Applying the left-hand rule, we find that the flow of current is toward us. In Fig. 12-4*f*, the motion of the conductor is upward, so the direction of the current flow is away from us. In Parts *g* and *h* of the figure, the motion of the conductor is parallel with the direction of the flux lines. The conductor does not cut across any lines of force, and the drawing thus shows that there is no current flow. Figure 12-4*i* shows no motion, either of the conductor or of the magnet and its magnetic field, so the drawing shows that there is no current flow.

12-3. ELECTROMAGNETIC INDUCTION

The method of producing electricity just described is called *electromagnetic induction.* We say that this method *induces* emf in the coil or conductor and that, as a result of this induced emf, a current flows in the coil or conductor. From your study of magnetism, you know that when magnetism is induced in a piece of magnetic material, it is done by placing the magnetic material in a magnetic field. So, when we say that an emf is induced, we mean that it is produced without electrical contact with the circuit in which it is induced.

The amount of emf produced by electromagnetic induction depends upon the speed with which a conductor cuts across

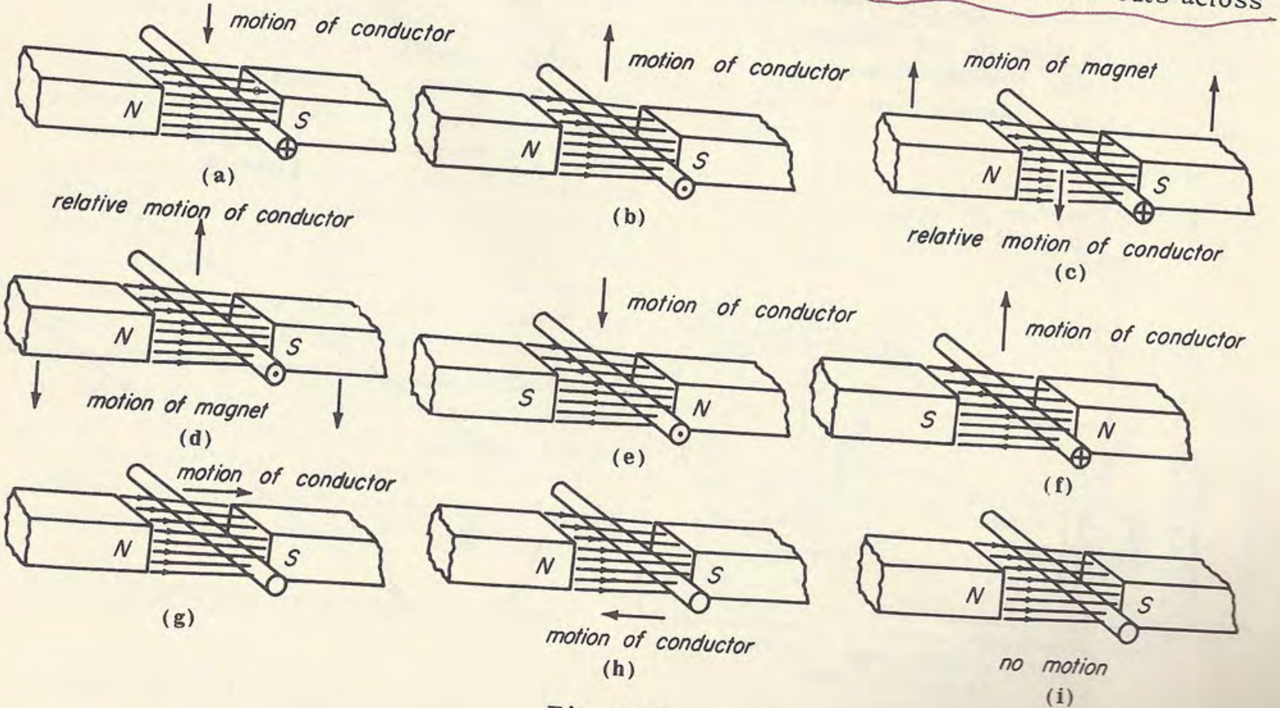


Fig. 12-4

magnetic lines of force. This means that the faster the flux lines cut the conductor or the conductor cuts across the flux lines, the greater is the induced voltage. Therefore, to increase the amount of induced emf, it is necessary to increase the number of flux lines cut per second by the conductor. Practically, we may do this in three ways:

1. By increasing the flux density (increasing the number of lines of force in a given space). This may be done by increasing the magnetic strength (shown in Fig. 12-5*a*) as is done in Fig. 12-5*b*.

2. By increasing the speed of the conductor. Doubling the speed of the conductor doubles the induced emf, as shown in Fig. 12-5*c*.

3. By increasing the number of conductors. This may be done by increasing the number of turns in the conductor that cuts the magnetic flux. Doubling the number of turns in the conductor doubles the emf induced, as shown in Fig. 12-5*d*.

The amount of emf induced in the moving coil of a generator may be found by using the

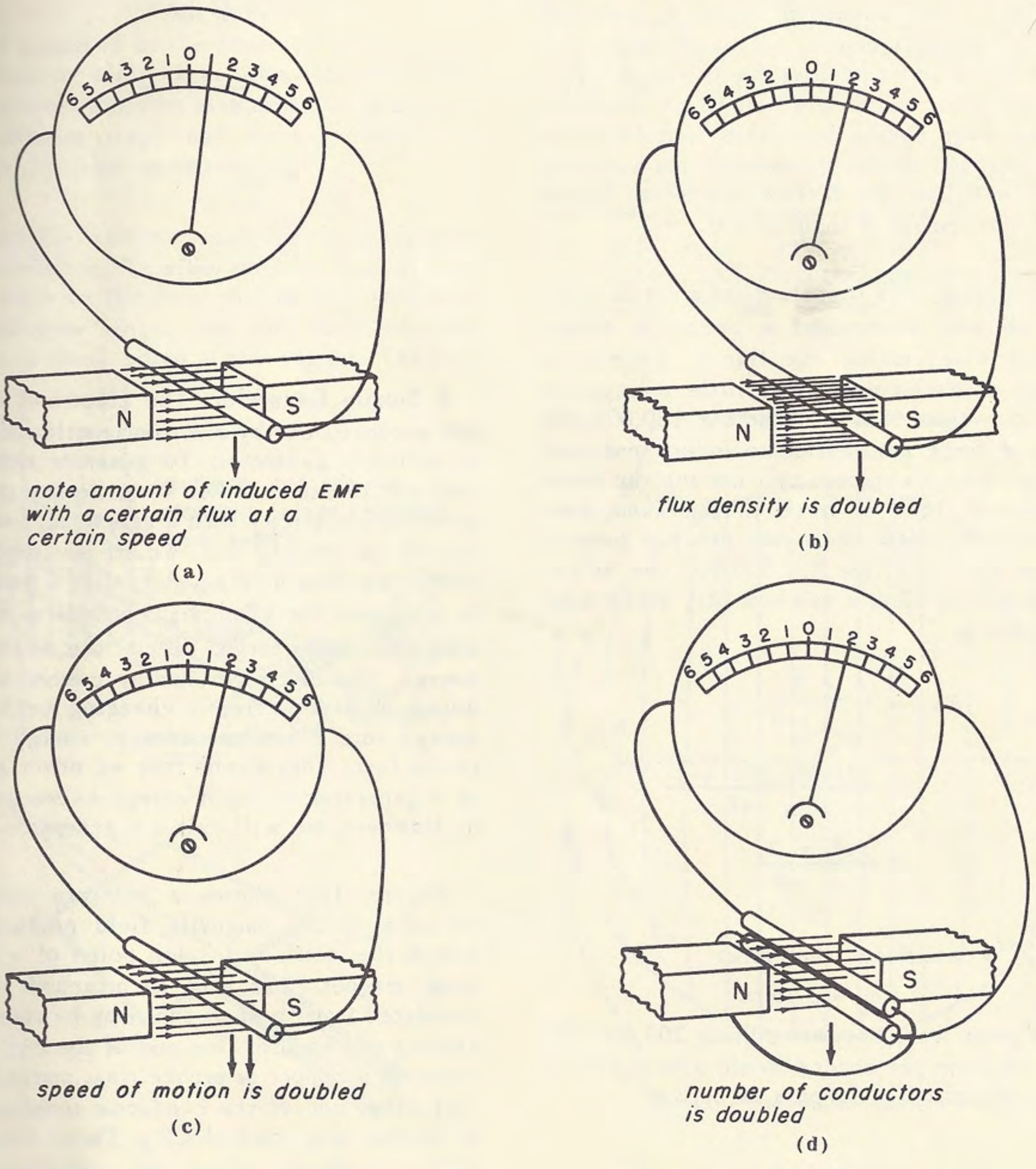


Fig. 12-5

following formula:

$$Emf = \frac{F \times N}{t \times 10^8}$$

where:

Emf = the average value of the voltage induced in the coil

F = the flux—the total number of lines of force cut by the coil

N = the number of turns in the coil

t = time in seconds

This is not supposed to be a practical formula for servicemen. What is more, you could spend an entire lifetime as a technician, working with radio and television circuits, without ever having seen this formula. It is only included in this lesson so that you may better see how the factors discussed above affect the amount of induced emf.

Let's break this formula down a bit in order that we may understand it better. A single turn of wire cutting one line of force in a second produces very, very little voltage. In fact, one turn of wire must cut 100,000,000 lines of force per second to induce one volt in the wire. A two-turn coil cutting the same number of lines of force in the same time induces two volts. From your study of powers of ten, you know that 100,000,000 may be expressed as 10^8. Let's see how this works with the formula:

$$Emf = \frac{F \times N}{t \times 10^8}$$

$$= \frac{100,000,000 \times 2}{1 \times 10^8}$$

$$= \frac{10^8 \times 2}{1 \times 10^8}$$

The 10^8's cancel out; therefore:

Emf = 2 volts

In the same way, one turn cutting 200,000,000 lines of force per second would also induce 2 volts. Applying the formula as before:

$$Emf = \frac{F \times N}{t \times 10^8}$$

$$= \frac{200,000,000 \times 1}{1 \times 10^8}$$

$$= \frac{2 \times 10^8}{1 \times 10^8}$$

2 volts

Let's see what happens when the speed of cutting is increased. Suppose a one-turn conductor cuts 100,000,000 lines of force in one half-second. Then:

$$Emf = \frac{F \times N}{t \times 10^8}$$

$$= \frac{10^8 \times 1}{0.5 \times 10^8}$$

$$= \frac{1}{0.5}$$

$$= 2 \text{ volts}$$

A Simple Generator. The electrical device that produces emf by electromagnetic induction is called a *generator.* To *generate* means to produce; to cause to be. When we say that we generate electricity with a generator, however, this is not strictly true. We are not producing electricity from nothing. Actually, a generator is a device for changing mechanical energy into electrical energy. Without the mechanical energy, the electrical energy cannot be produced. What is more, in changing mechanical energy into electrical energy, energy is actually lost. This means that we never get out of a generator as much energy as we put into it. However, we still call it a generator.

Figure 12-6 shows a one-turn conductor rotating in the magnetic field produced between the north and south poles of a permanent magnet. The coil is attached to, and insulated from, a shaft that may be rotated by turning the handle. One end of the coil terminates in a copper or bronze ring, marked CR_1. The other end of the conductor terminates in a similar ring marked CR_2. These rings are called *collector rings*, or sometimes *slip rings*. They are called collector rings because

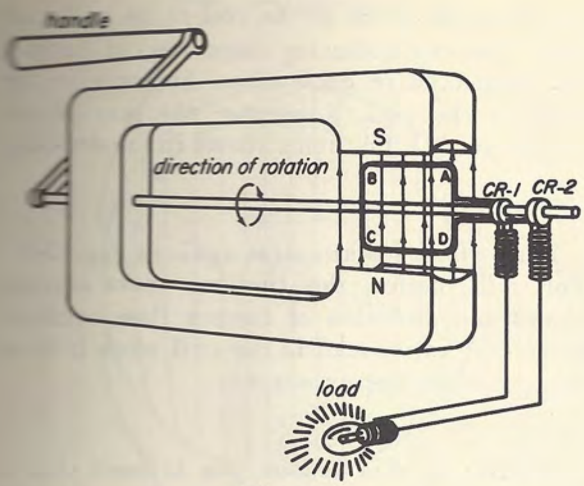
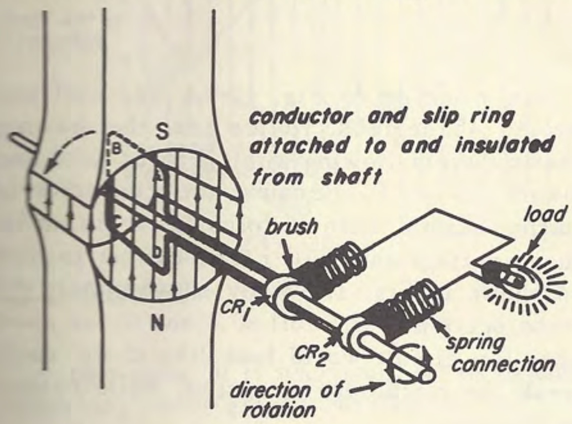


Fig. 12-6

the emf produced by the generator is collected from them by sliding contacts. These sliding contacts are called *brushes*; they press against the collector rings and make contact with them as the drive shaft rotates.

Figure 12-7*a* shows another view of the one-turn conductor. This is more or less a front view, showing the front end of the shaft, with the collector rings, the coil, and only the north and south poles of the magnet. The coil



(a)

(b)

Fig. 12-7

is shown in the same position with respect to the poles as in Fig. 12-6.

Note that the poles are shaped so that the coil may rotate between them without touching them. The arrows indicate that the coil is rotating in a counterclockwise direction. In Fig. 12-7*b*, the coil has made a quarter rotation and is in a horizontal position.

In order to follow the action of a generator producing electricity, you must concentrate your attention on some very small but important details. So, although the drawings in Fig. 12-6 and 12-7 are fairly simple, we need some even simpler drawings.

One such drawing is 12-8, which shows the coil in the same position as in 12-7*b*. However, this drawing shows only the two poles, the direction of the flux, the direction of the movement of the coil,

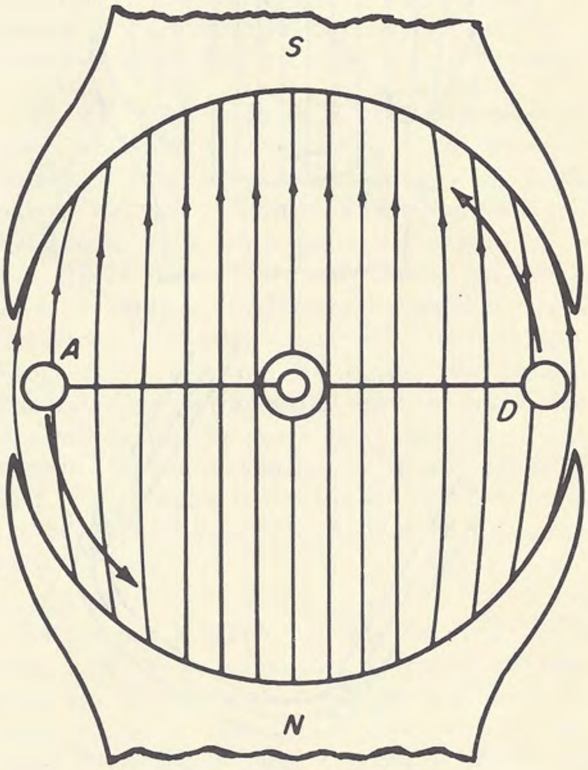
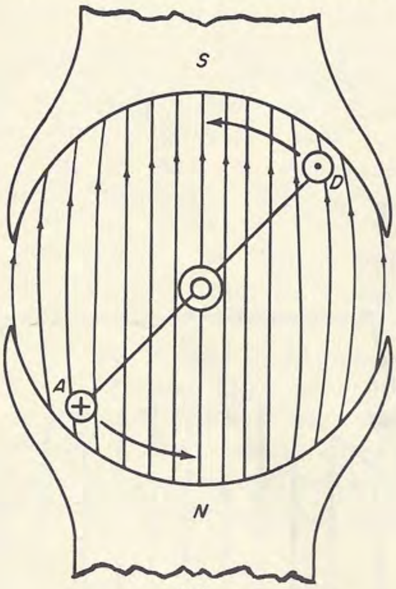
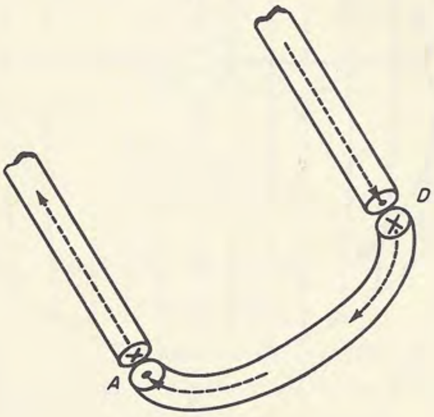


Fig. 12-8

and the coil itself. The coil is represented by two circles connected by straight lines to two more circles. Because we will use this kind of drawing in the explanation that follows, it is important that you know exactly what is meant by these circles and straight lines. The circle marked *A* represents the part of the winding of the coil which is shown going from *A* to *B* in Fig. 12-7*b*. It is supposed to be a cross section of the wire. The reason a cross-section is shown is so that you may see the direction of current flow inside the coil. The straight line that connects *A* to the smaller of the center circles represents the connection between the *A*-end of the coil and its collector ring. *D* represents the other part of the coil, shown in Fig. 12-7*b* as running from *C* to *D*, and the straight line connecting it to the larger of the center circles shows the connection from the *D*-end of the coil to its collector ring. The two collector rings are, of course, not connected to each other, but only to the ends of the coil. Remember the rest of the coil is used; it just isn't shown in the drawing.



(a)



(b)

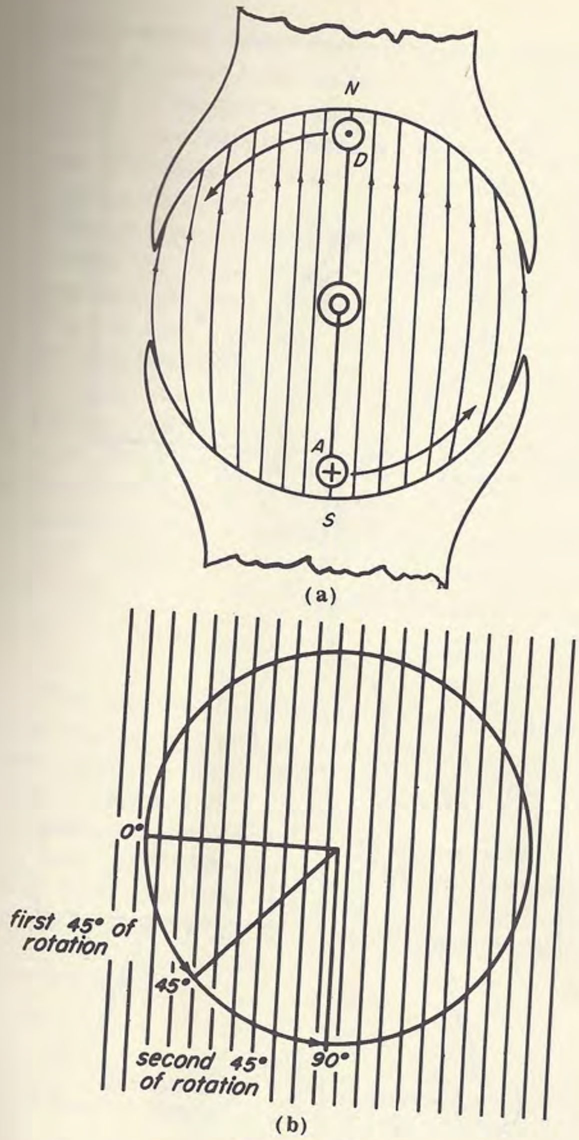
Fig. 12-9

Let's direct our attention again to Fig.12-8 . You will notice that neither cross section shows the direction of current flow because no voltage is induced in the coil when it is in this position. Let us see why.

Earlier in this lesson you learned that a voltage is induced when either the conductor moves across the lines of force or the lines of force move across the conductor. When the coil is in the position shown in Fig. 12-8 , the arrows show that the coil is moving. However, take a very close look at one end of this coil. For a very short time, the movement of the coil, as shown by the cross section *A*, is parallel with the flux lines. Thus, for this very short time, neither *A* nor *D* is cutting across the lines of flux. And, with no flux lines being cut, there is no induced voltage.

Now move on to Fig. 12-9*a*. The coil has rotated 45 degrees. Notice that the drawing shows current flowing away from us at *A* and toward us at *D*. Because the conductor is cutting across lines of force, there is an induced voltage that will cause current to flow as shown in Fig. 12-9*b*. By showing only the cross section of the coil at *A* and *D*, we show what the circuit would look like if we could break the circuit for an instant while current is flowing.

In Fig. 12-10*a*, the conductor is shown in a vertical position. At this point, the induced emf is maximum. The reason for this may be found by looking at the parallel lines shown in Fig. 12-10*b*. You will note that fewer lines are cut during the first 45 degrees of rotation than during the second 45 degrees of rotation. The greatest number of lines is cut when the conductor is at right angles to the lines of force.



(a)

(b)

Fig. 12-10

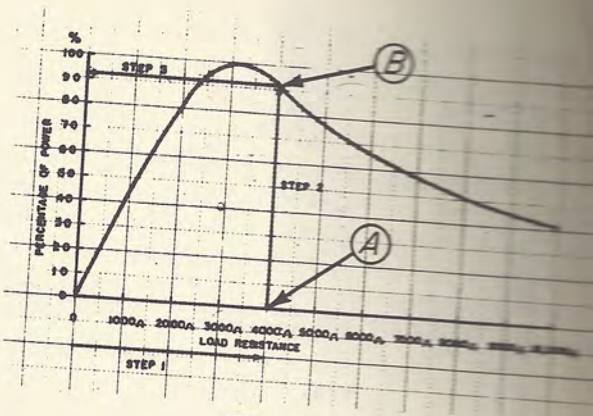


Fig. 12-11

12-4. GRAPHS

At this point, it is necessary for us to know something about *graphs*, so that we may continue our study of generators. Without this knowledge, the next steps in the study of generators become very difficult. A graph is a diagram that shows how one quantity depends on or changes with another quantity. You must have noticed how often drawings, diagrams, and pictures are used in these lessons to help you understand the action of circuits and the parts that make up circuits. A graph is just another diagram—one that takes the place of a lot of figures. A graph usually is easier to understand than a series of figures would be, because the changes in quantities that take place may be seen and understood almost at a glance.

One of the most popular kinds of graph is the *line graph*. Figure 12-11 shows such a graph. It shows the relative power output of a battery for different values of load resistance. The power is marked off in percentages on the line that runs up and down, which we call the *vertical axis* or, sometimes, the *Y axis*. The load resistance is marked off in steps of 1,000 ohms on the line that goes across the page, which we call the *horizontal axis* or, sometimes, the *X* axis. The line formed in making this graph is called a *curve*. Such lines are not always curved; in fact, they may be irregular or even straight. No matter what shape they may have, they are always called curves.

We use such a graph in this manner. Suppose we want to know how much power is delivered when the load resistance is 4,000 ohms. We first find the 4,000 point on the horizontal axis; this point is marked *A* in Fig. 12-11. From this point on the horizontal axis, we draw a line vertically until it meets the curve. This point is marked *B* on the graph. From this point on the curve, we draw a straight line horizontally until it meets the vertical axis. We find that this line falls one-fifth of the way between 90 and 100%, or 92%. So we know that with a 4,000-ohm load, the battery delivers 92% of its maximum power output.

We say of a graph like that in Fig. 12-11 that it is drawn to scale, which means that each unit on either axis is represented by the same length of line as any other unit on the same axis. When such a graph is drawn on graph paper, it is easy to locate points on either axis that lie between those that are

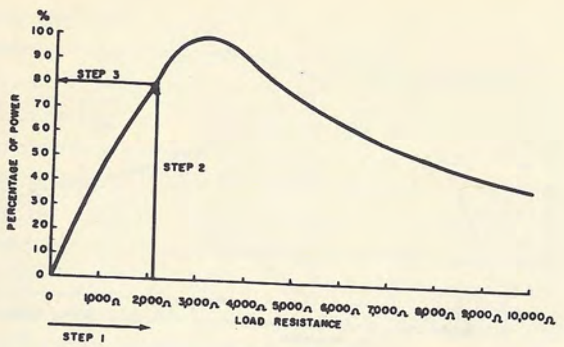


Fig. 12-12

marked off. For example, each line that meets the horizontal axis between the 1,000-ohm points represents a 100-ohm step, and each line that meets the vertical axis represents a 2-percent step.

However, it is not necessary to draw such a graph on graph paper. The same information may be obtained when the graph is drawn as it is in Fig. 12-12. When drawn in this manner, graphs are a little more difficult to read accurately than those drawn on graph paper. Let us suppose that we want to know the relative power output of the battery when the resistance of the load is 2,100 ohms. We first find the 2,000-ohm mark and then continue one-tenth of the distance between this point and the 3,000-ohm mark. From this point, we draw a line perpendicular to the horizontal axis until it meets the curve. From this point on the curve, we draw a horizontal line to the vertical axis. We find that this line meets the vertical axis at the 80-percent point. The power, therefore is 80 percent.

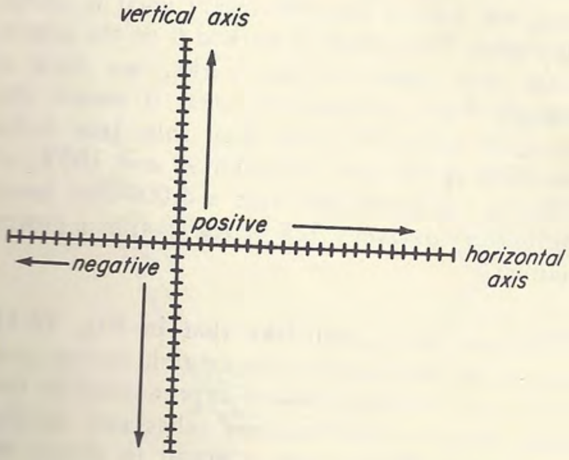


Fig. 12-13

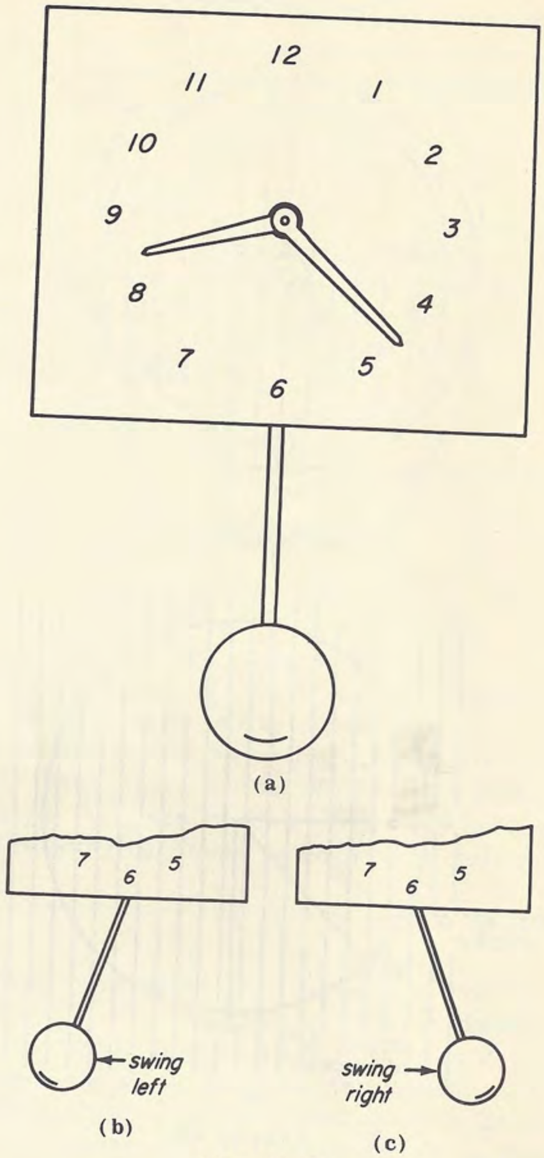


Fig. 12-14

Extending the Axes. The vertical axis may be extended below the horizontal axis, and the horizontal axis may be extended beyond the vertical axis, as shown in Fig. 12-13. The point where the horizontal and vertical axes intersect (come together) is usually considered zero for both axes. Any point on the vertical axis *above* the horizontal axis is considered *positive* in value and direction. Any point on the vertical axis *below* the horizontal axis is considered to be *negative* in value and direction. All values on the horizontal axis to the left of the vertical axis are considered *negative* in value and direction, and those to the *right*, *positive* in value and direction.

Let us see how such a graph is used to

show values where there is a change in direction. Figure 12-14*a* shows a clock with a pendulum. The clock has stopped; the pendulum is in a position of rest. When the clock goes, the pendulum swings back and forth at a regular rate. Once in every second, it moves through the position of rest to the left as shown in Fig. 12-14*b*, returns through the position of rest to the right, as shown in Fig. 12-14*c*, and back to the position of rest. In each succeeding second, it makes a similar swing to the left and to the right. Figure 12-15 shows graphically the amount of movement in each direction as the pendulum swings through one complete cycle of motion. Time is shown on the horizontal axis. Because the complete cycle occurs in one second, the horizontal axis is marked off in hundredths of a second.

The amount of movement of the pendulum in one direction and then the other is shown on the vertical axis. We cannot say that the movement either to the left or to the right is negative. It just doesn't make sense. However, in order to show this movement on the graph, we can mark the vertical axis above the horizontal axis as *right* and below the horizontal axis as *left*. This is what the draftsman did when he drew the curve of Fig. 12-15.

Looking closely at this curve, you can see that it is possible to determine the amount of movement either to the left or to the right from the zero position at any portion of a second. The vertical lines drawn to the curve from the horizontal axis represent the amount of movement from the zero position at several instants in the first part of the cycle.

The curve of Fig. 12-15 is the same as some of the waveforms that you saw in Theory Lesson One. We call it a *sine curve or sine wave*. You will see and use a sine wave many times in this course. It is sometimes used as a symbol for cycles per second. For example, 500 cps can be written 500 ~.

12-5. SIMPLE A-C GENERATOR

The simple generator that you studied earlier in this lesson produces alternating current. To prove this, let us see what happens to the direction of current and the amount of current flow during one rotation of the

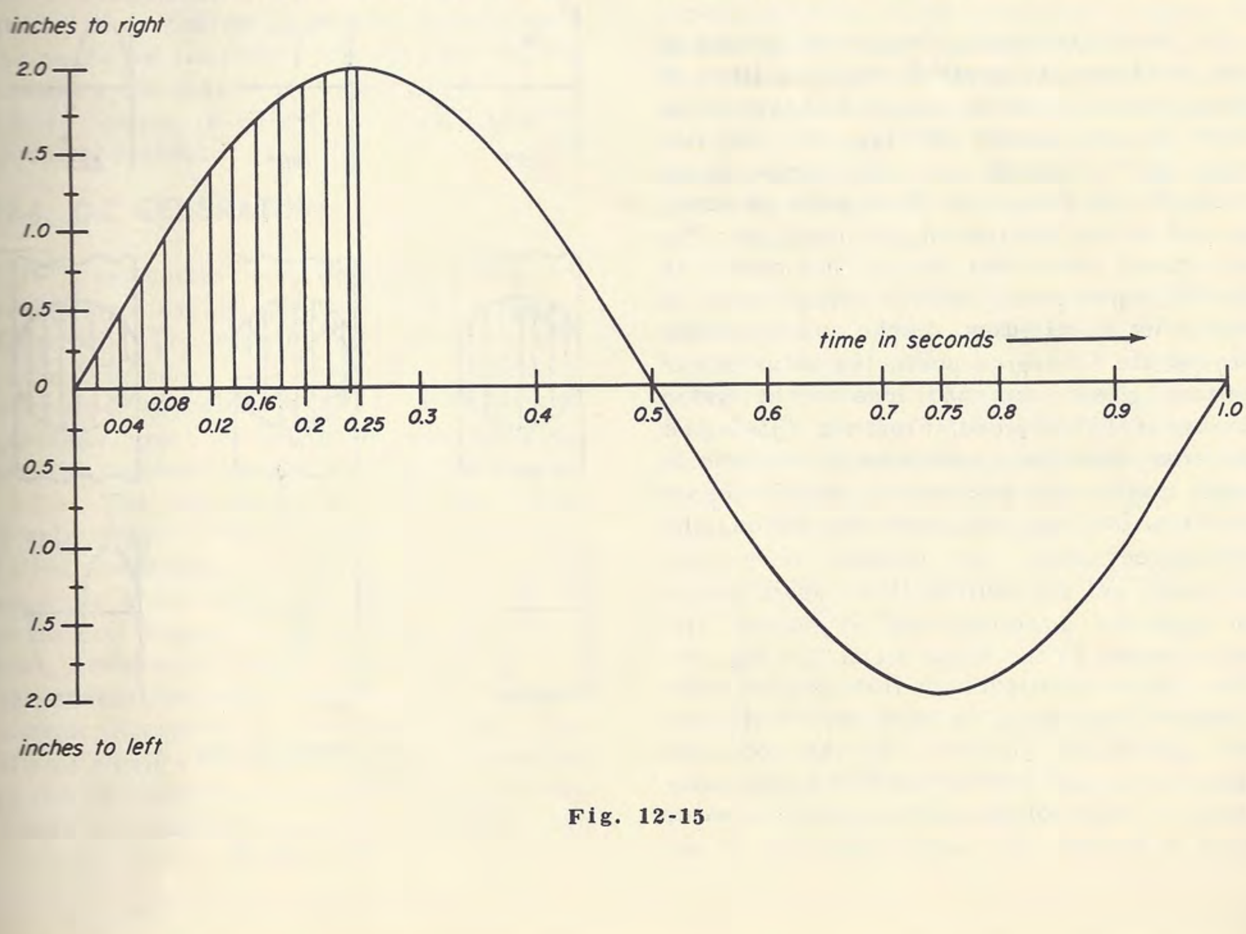


Fig. 12-15

coil. Examine Fig. 12-16, which shows a complete rotation of the coil in the magnetic field and the amplitude of voltage for each 45 degrees of rotation. This series of drawings shows only the current flowing in cross section *A* of the coil. This is so that we may follow the changes that take place through one rotation, or one *cycle*, as it is called. Just bear in mind that the direction of the flow of the current at cross section *D* is opposite to the direction of flow at cross section *A*.

Starting with *A*, in zero position, we follow its rotation in nine drawings. The graph below each drawing shows the amplitude of induced voltage and direction of current flow for each 45 degrees of rotation. The horizontal axis is marked off in degrees of rotation. The position on the vertical axis where it meets the horizontal axis represents zero voltage. Any point above the horizontal axis represents an amplitude of voltage of given polarity, and any point below the horizontal axis represents an amplitude of voltage of opposite polarity. In each of these graphs, the position of the black dot shows the direction of the current flow.

In the first drawing, where the motion of the conductor is parallel with the lines of force, the value of the voltage is shown to be zero. In the second drawing, the coil has rotated 45 degrees, and the instantaneous value of the voltage at 45 degrees is represented by the position of the black dot. The next panel shows that the coil has rotated to the 90-degree point, and the voltage value at this point is maximum. As the coil continues beyond the 90-degree point, the value of the voltage grows less and less to the value shown at 135 degrees. From the 135-degree position, the voltage continues to decrease in value until it reaches zero at the 180-degree position. As the coil continues beyond the 180-degree point, the polarity of voltage reverses and the current flows again but in an opposite direction until it reaches the value shown by the black dot at 225 degrees. The current continues to flow in this same direction, increasing in value until it reaches the 270-degree position. As the coil continues to rotate beyond the 270-degree position, the value of current decreases in value until it reaches the amount indicated at the 315-degree position. As the coil completes the first cycle, the current gradually decreases to the zero voltage point at 360 degrees.

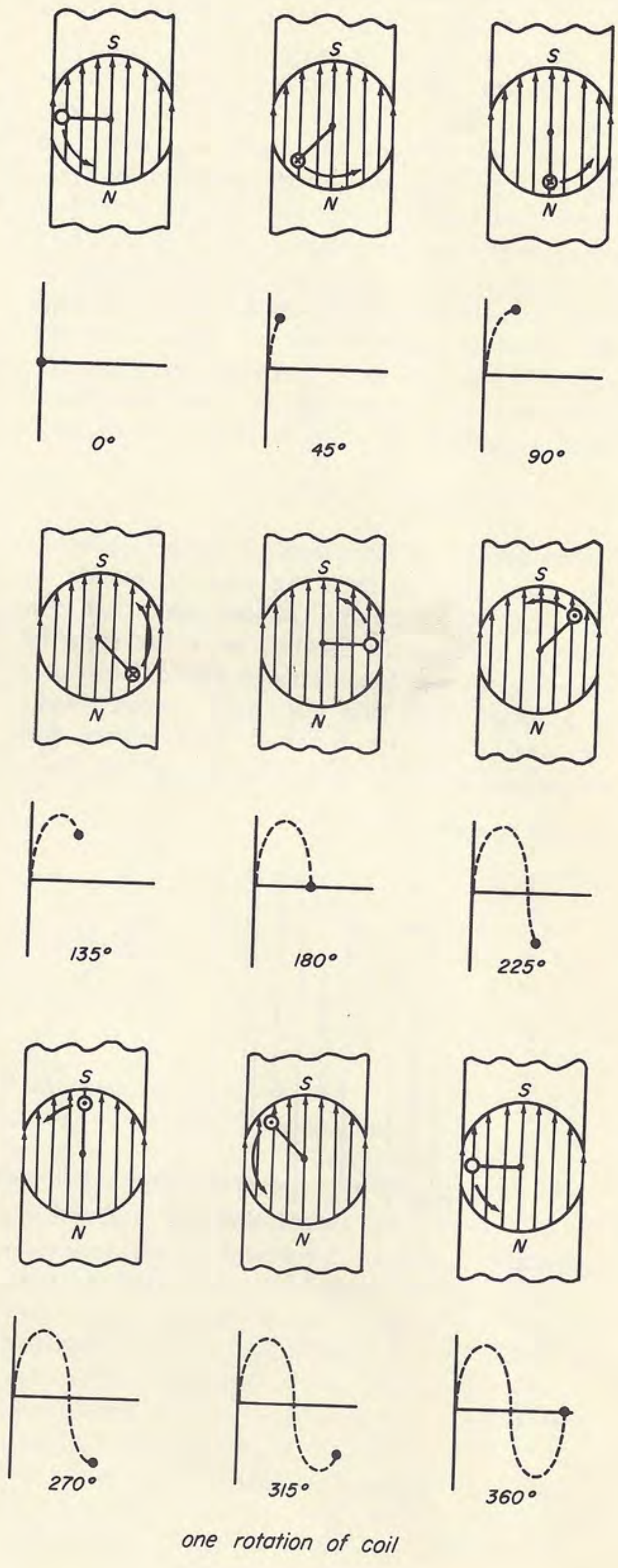


Fig. 12-16

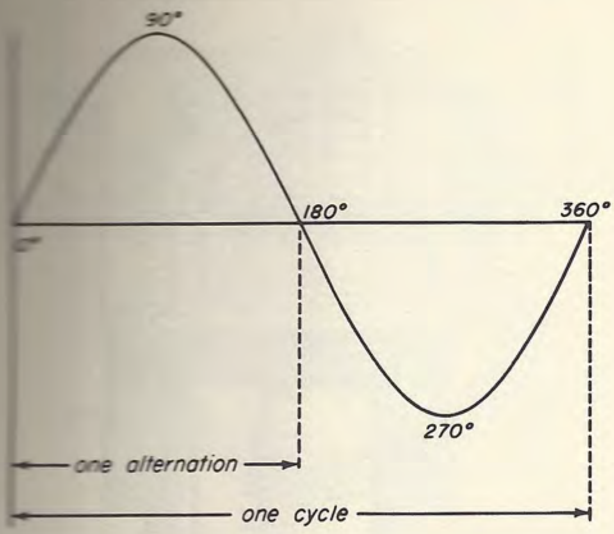
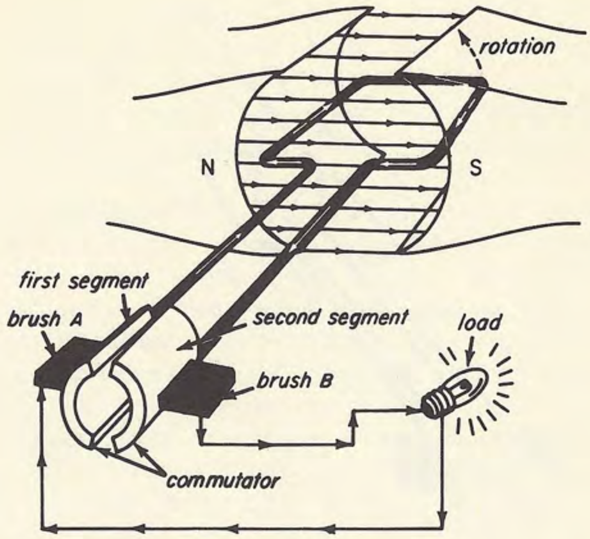


Fig. 12-17

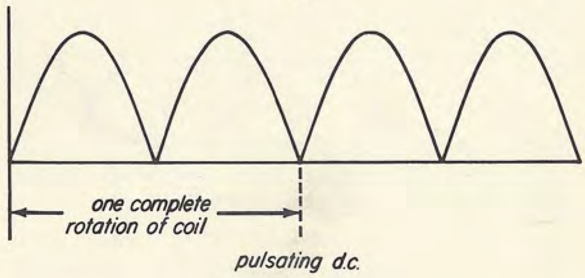
By joining together all of the instantaneous values of voltage obtained in one rotation, or cycle, we produce a sine wave, as shown in Fig. 12-17. Of course, the coil continues rotating; but just so long as the coil moves at the same speed, each rotation will produce the same waveform in the same period of time. All the changes that occur in one direction, either above or below the horizontal axis, during one cycle, make up an *alternation*; there are two alternations to one cycle. The frequency of an alternating current depends upon the number of complete cycles per second. For example, the standard for a-c power, in the United States, is 60 cycles, or 120 alternations per second.

12-6. D-C GENERATORS

D-C generators are very much like a-c generators, except for one very important difference. The rotating coil of a d-c generator terminates in a *commutator* instead of in a pair of collector rings. A single-coil generator, such as we have been studying, uses a commutator like that shown in Fig. 12-18*a*. The commutator shown is made from a split copper ring. The two split sections, called *segments*, are insulated from each other by a nonconducting material. One end of the coil terminates in one segment, and the other terminates in the other segment. Two carbon brushes make contact with the commutator segments as the coil rotates. For almost a half a rotation, brush *A* is connected to the number-one segment of the commutator. Then, as the coil continues to rotate, the



(a)



(b)

Fig. 12-18

second segment of the commutator comes in contact with brush *A*. Each half-cycle, the commutator switches the coil connections to the two brushes, so that each brush always receives current in the same direction. The waveform of the current flowing in the outer circuit is as shown in Fig. 12-18*b*. This is called *pulsating d.c.*

Pulsating d.c., while it rises and falls in value, always flows in the same direction. However, the pulsating d.c. from a single-coil generator doesn't look or act much like the d.c. we get from a battery. The d.c. that we obtain from a battery in good condition has a constant value and can be represented by a straight line, as shown in Fig. 12-19.

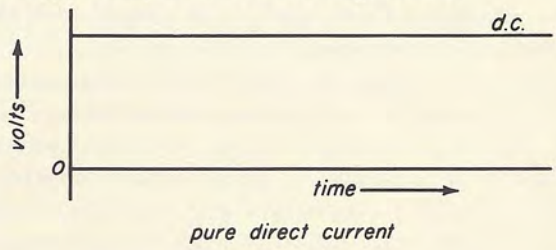
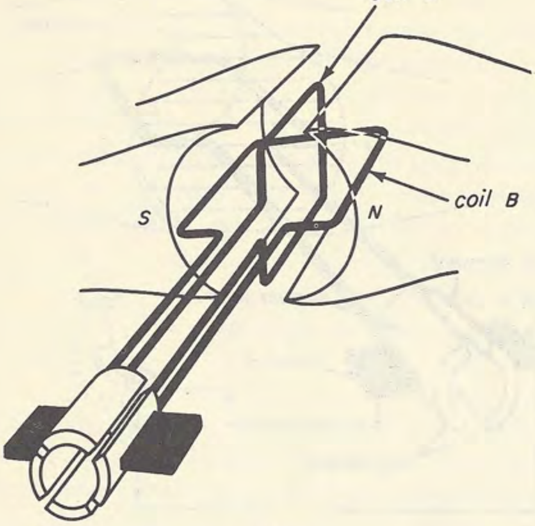
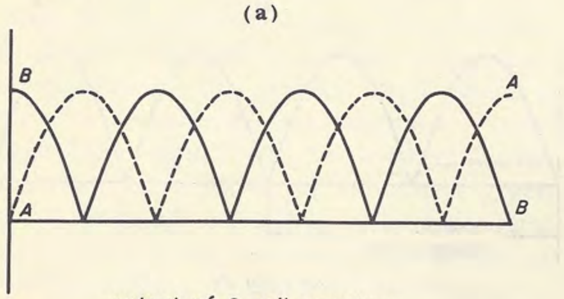


Fig. 12-19

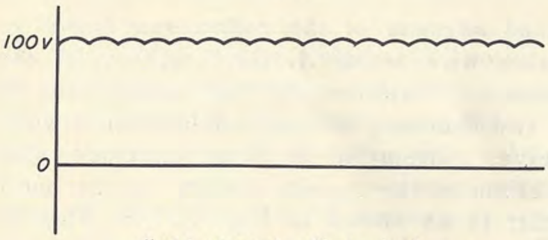


(a)



output of 2-coil armature

(b)

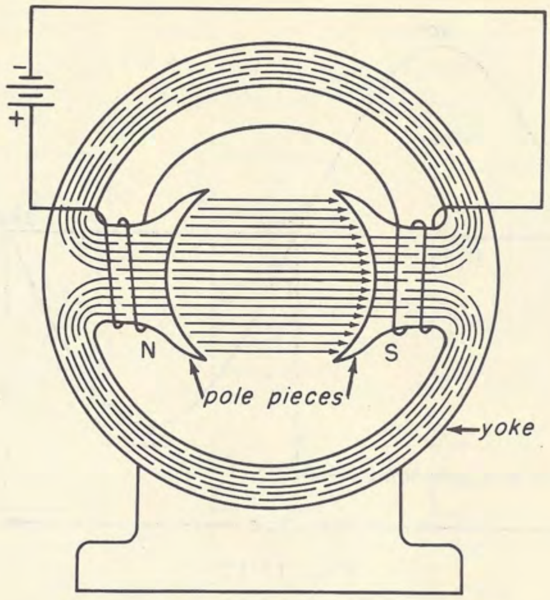


direct current with a ripple

(c)

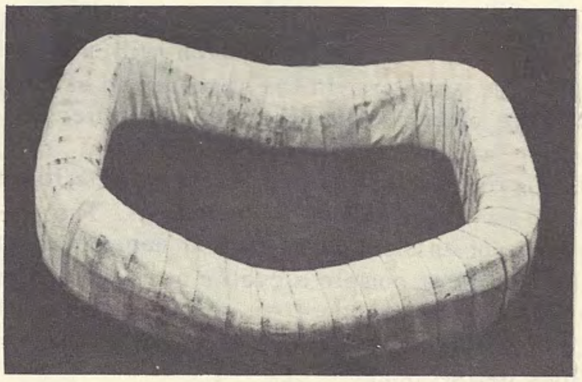
Fig. 12-20

The ideal d-c generator is one that produces d.c. of a constant value, such as that shown in Fig. 12-19. However, such a generator does not exist among the electromagnetic types. However, we can improve the output waveform by increasing the number of armature coils. For example, if two coils are placed at right angles to each other, as shown in Fig. 12-20*a*, and the armature is allowed to rotate, when coil *A* is in the zero-voltage position, coil *B* is in the maximum-voltage position. Later, when coil *B* reaches zero-voltage position, coil *A* is in maximum-voltage position. Each coil has two ends, so a two-coil d-c generator requires a four-section commutator. As you can see in Fig. 12-20*b*, the waveform of coil *A* is maximum when wave *B* is minimum, and wave *B* is maximum when wave *A* is minimum. Thus, the voltage does not fall to zero. To improve the waveform still further, we can add more coils. The more coils that we use in the armature, the less is the variation in the output waveform. Thus, from a practical d-c generator, we may get a waveform like that of Fig. 12-20*c*. This is no longer a pulsating d.c. We say that it is a d.c. with a *ripple*. The *ripple* is the small variation that still remains in the waveform.



seperately excited generator field

(a)



(b)

Fig. 12-21

12-7. PRACTICAL GENERATORS

In our discussion of generators and generator action, we have assumed that the

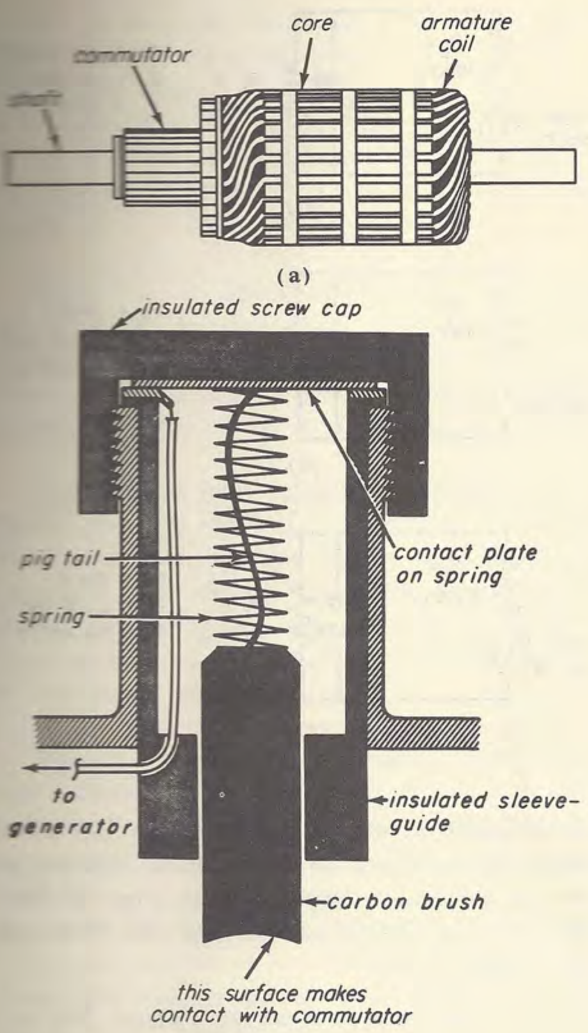


Fig. 12-22

source of flux was a permanent magnet. Most generators do not use a permanent magnet to produce the magnetic field. Instead, electromagnets are used. Figure 12-21*a* shows a generator frame, called a *yoke*, with electromagnets mounted in place. The drawing shows only a couple of turns of wire wound around each pole piece. The actual *field coils* (as they are called) of a practical generator contain either many turns of heavy-duty wire or a much greater number of turns of finer wire. The field coils are wrapped with insulating tape and look like those shown in Fig. 12-21*b*.

The source of voltage for the field coils is shown as a battery. We say of such a field that it is *separately excited*. A-C generators require separate excitations because they deliver only a.c. If a.c. were to be fed to the field coils, the polarity of the field would change constantly. This is undesirable. We want only the rotation of the armature to cause alternations of the output. So a source of d.c. usually a separate d-c generator, is used to excite the field of a-c generators.

In d-c generators, on the other hand, field excitation is generally provided by feeding back into the field coils a portion of the emf produced by the generator. This is called *self-excitation*. In such cases, the excitation of the generator field, when first starting, may be obtained from the residual magnetism that exists in the core of the electromagnetic field coil. In cases where there is not sufficient magnetism in the core, as when the generator is placed in service for the first time, or has not been in use for a long period of time, it is necessary to provide excitation from a battery or other d-c source when the generator is first started.

Up until now we have studied only simple coils, rotating in a magnetic field. Figure 12-22*a* shows the *armature* of a d-c generator. The armature is the name of the complete assembly. It includes the shaft, the armature coil, the core material, and the commutator. Figure 12-22*b* shows a carbon brush and its mounting, such as is used in making contact with a rotating commutator.

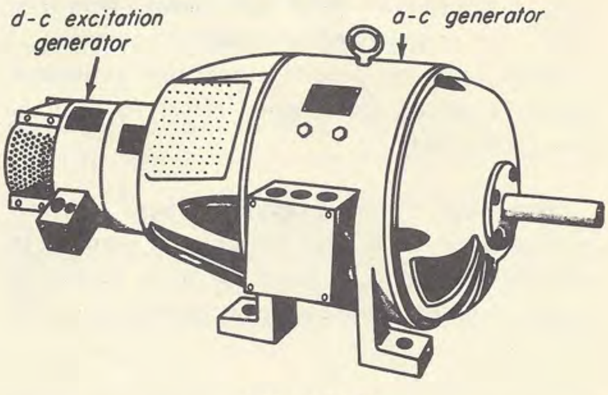


Fig. 12-23

In low-power a-c generators, the a.c. induced in the armature coil may be taken from the collector rings by brushes. However, in high-power commercial a-c generators, the amount of current passing through the brushes would be excessive. For this reason, heavy duty a-c generators use stationary armature coils, and the electromagnetic fields rotate, with brushes supplying the field excitation. Figure 12-23 shows an alternating current generator with a rotating field excited by a small d-c generator mounted next to it.

Internal Resistance. In our study of primary and secondary cells, we found that some of the emf produced by chemical action was lost because of internal resistance. For the same reason, the terminal voltage of any generator of the type we have studied in this lesson will be less than the induced emf. The internal resistance of such generators causes a voltage drop inside the generator whenever a load is applied to its terminals. The internal resistance of a generator is caused by the resistance of the armature coil, the resistance of brushes, and, in a self-excited generator, by the resistance of the field coil.

Loads. When you think of a generator or of generator action, remember that a generator changes one form of energy into another form of energy. We put in mechanical energy and out comes electrical energy. This means, therefore, that it takes work to make a generator produce electricity, and the greater the load on the generator, the greater is the effort required to operate it. For example, the armed services use a combination radio receiver and transmitter, powered by a hand generator. When the receiver section is operating, there is very little load on the generator, and it is easy to turn the generator shaft. However, when the transmitter section is operating, a greater load is placed upon the generator, and it requires much more effort to turn the generator shaft.

Maximum Power Transfer. When a generator is used to deliver power to a load, it is usually desirable to have as much power as possible transferred from the generator to the load.

It is not possible to get all of the generated power into the load, because some of it is used up in the internal resistance of the generator. Let us see how maximum power transfer can be obtained.

You know that any source of electrical power, whether it is a battery or a generator, has internal resistance. Let us consider a generator with an internal resistance of 1,000 ohms, as shown in Fig. 12-24. We will place

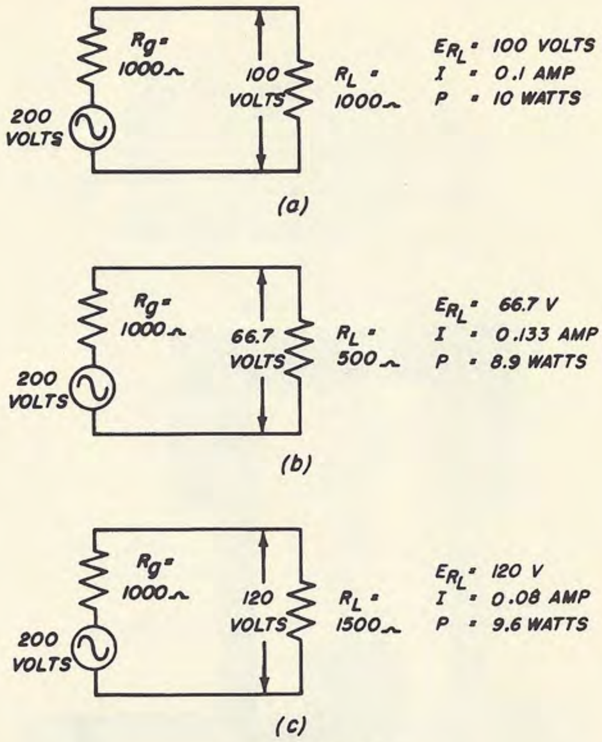


Fig. 12-24

three loads across this generator. The first load will be equal to the internal resistance of the generator, as shown in Fig. 12-24*a*. We can use Ohm's Law to see the effect of this load.

In effect, this is a series circuit. The resistance of the load is considered to be in series with the internal resistance of the generator. The voltage across these two resistors in series is the 200 volts supplied by the generator. You probably can see at once that, since the two series resistors are equal, the voltage drop across each one is half the total applied voltage, or 100 volts. You can find the current across the load resistor R_L by Ohm's Law:

$$I = \frac{100}{1,000} = 0.1 \text{ amp}$$

To find the power delivered to the load, you use the following power formula:

$$P = EI$$

Therefore, the power delivered to the load is:

$$\begin{aligned} P &= E_{RL} \ I_{RL} \\ &= 100 \times 0.1 \\ &= 10 \text{ watts} \end{aligned}$$

If the load on the same generator is reduced to 500 ohms, as shown in Fig. 12-24*b*, the power delivered to the load will be only 8.9 watts. You can prove this by performing the same type of calculation that was used for finding the power delivered to a 1,000-ohm load.

Likewise, if you calculate the effect of placing a 1,500-ohm load across the same generator in place of the 1,000-ohm load, as shown in Fig. 12-24*c*, you will find that the power delivered to the load is only 9.6 watts.

Although we have made only three calculations, you will find, if you wish to try other values of load, that no matter what load resistance you choose, maximum transfer of power occurs when the resistance of the load is the same as the internal resistance of the power source.

You will learn in later lessons that tubes and antennas are also considered to be power sources, and that the load resistance has to be matched to the resistance of the source for maximum transfer of power. Right now, remember this important rule: *For the most efficient transfer of power from a source to a load, the resistance of the load should be equal to the internal resistance of the power source.*

12-8. TRANSFORMERS

In the early days of commercial electric-power generators, the voltage supplied to homes, offices, and factories was d.c. Today, however, most of the commercially produced electrical power is a.c. There is good reason for this. When d-c power is supplied to a home or other building far from the generating plant, so much voltage may be lost in the power lines (due to resistance) that the voltage available at the receiving end may be too low to operate electrical equipment satisfactorily. So, unless the d-c power source is nearby, it is difficult to obtain electric power at a useful voltage. The voltage of a-c power, on the other hand, may be raised or lowered to any useful value by means of a *transformer.*

A transformer is a device, without moving

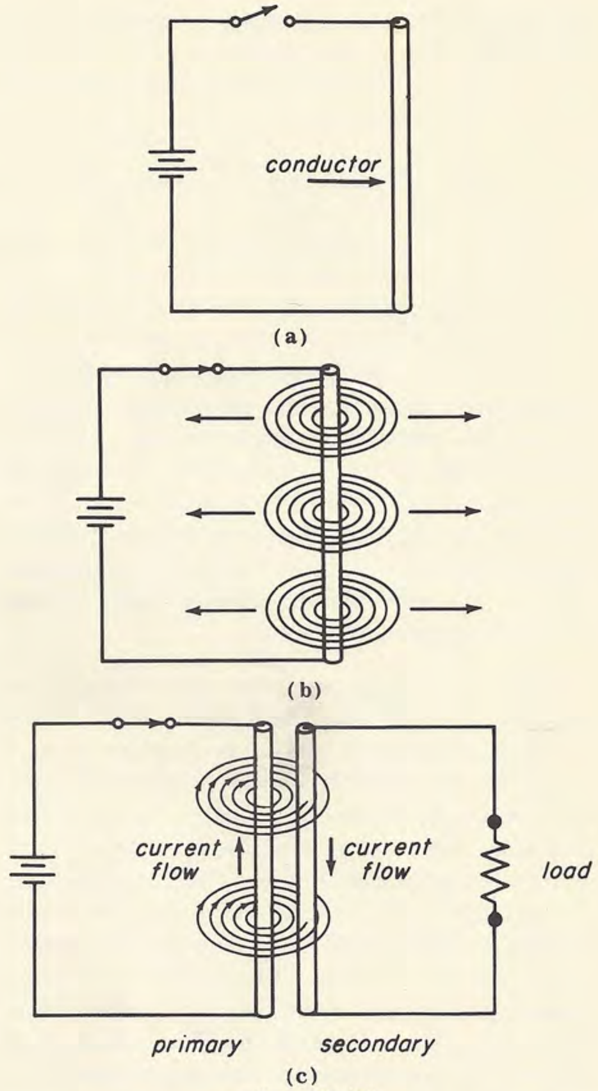


Fig. 12-25

parts, that transfers electricity from one circuit, called the *primary,* to another circuit, called the *secondary,* by means of electromagnetic induction. Many kinds and sizes of transformers are used in radio and television receivers. Some transformers are used to raise a voltage from one value to another. Such transformers are called *step-up* transformers. Other transformers are used to lower a voltage to some needed value. These are called *step-down* transformers. Transformers are so widely used that it pays to know how they work.

While transformers normally operate on alternating current, we will start our study of transformer action by considering what happens when d.c. is applied to a conductor. Figure 12-25*a* shows a conductor connected in series with a switch (in the open position). This circuit is connected to a battery. From your study of electromagnetism, you know that when the switch is closed, a magnetic field will form around the conductor, as shown in Fig. 12-25*b*. You know, too, that the field grows and the flux moves out from the conductor, as shown by the small arrows, until the current reaches its maximum value. If another conductor is placed close to the first conductor as shown in Fig. 12-25*c*, the flux moving out to form the field will cut the turns of this second conductor. When this happens, a voltage is induced in the second conductor while the field is being formed. If a load is placed across the second conductor, or if the circuit is otherwise completed, the induced voltage will cause a current to flow in the conductor until the field stops growing. Note that the direction of the current that flows in the secondary, as the result of the induced emf, is opposite in direction to the current flow in the primary circuit.

When d.c. is applied to the primary, the induced voltage and the current flow in the secondary last for only the instant that it takes for the current in the primary to reach its maximum value. From then on, the flux lines are stationary, and there is no relative motion between the flux and the secondary, so no voltage is induced. When the switch is opened, the field collapses and the flux moves back into the primary, which causes another instantaneous voltage to be induced and current to flow in the secondary. The direction of secondary current flow is then opposite to the direction of the secondary current when the field was forming.

A single conductor does not have as strong a field as does a coil. In order to increase the flux (and the induced emf), we can use a pair of coils, as in Fig. 12-26. The number of flux lines formed in this transformer depends on the number of turns in the primary and the amount of current flowing in the primary winding.

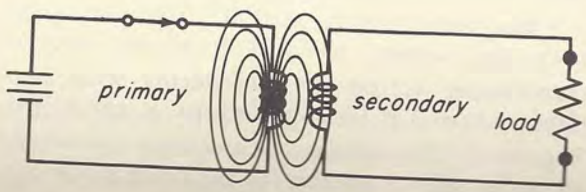


Fig. 12-26

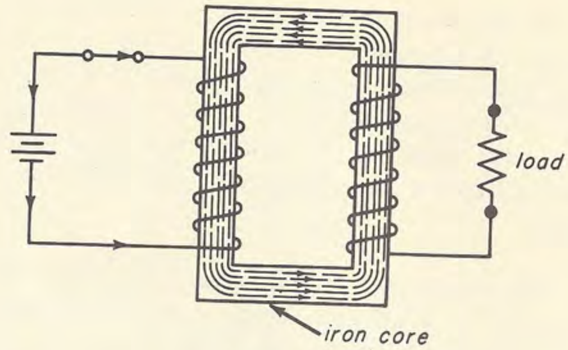


Fig. 12-27

Leakage Flux. Look at Fig. 12-26. Notice that only part of the flux lines actually cut the secondary. As a result, the greater number of flux lines are wasted because they do not contribute to the induction of voltage in the secondary. We call this *leakage flux*. In order to reduce the amount of leakage flux to a minimum, some transformers are wound on iron cores, as shown in Fig. 12-27. When this is done, practically all of the flux lines formed by current flowing in the primary cut the turns of the secondary. As a result, there is little or no leakage flux.

Practical Transformer Action. Pure d.c. applied to the primary of a transformer produces only a momentary current flow in the loaded secondary. Then, until the primary circuit is opened, no further change occurs in the secondary. The current flowing in the primary then produces only heat, which, if the d-c voltage is great enough, may cause the insulation on the primary to burn, and may even cause the wire of the primary to melt. It is possible to apply an interrupted d.c. to the primary to induce an a-c voltage in the secondary. You will learn how this may be done when you study vibrators and auto-radio power supplies. Most practical transformers operate on a.c.

Suppose that 60-cycle a.c. is applied to the primary of a transformer, as in Fig. 12-28. Then, with every alternation, the current flowing in the primary will rise and fall and cause the magnetic field to expand and contract. With 60-cycle current, this happens 120 times a second, as the primary current changes direction twice in each cycle. The emf induced in the secondary causes the secondary current to change direction at the same rate. It has the same frequency as the primary

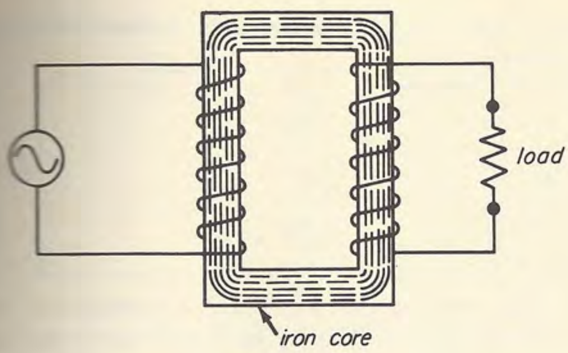


Fig. 12-28

voltage. The voltage induced in the secondary rises and falls as the voltage applied to the primary rises and falls. The only difference between the two voltages is that they are always opposite in polarity, and the currents that flow in each winding are opposite in direction. However, if the winding direction of the secondary is reversed, current direc- and voltage polarity become the same as the primary.

Turns, Voltage, and Current Ratios. The amount of voltage induced in the secondary of a transformer depends on the number of turns in the secondary winding and the number of flux lines that cut the secondary turns. The number of flux lines that cut the secondary depend on the number of turns in the primary and the voltage across it. So, we find that there is a fixed relationship between primary and secondary turns and between the primary voltage and the secondary voltage. For example, if the secondary has twice the number that the primary has, then the secondary voltage will be twice that of the primary. Or, if the secondary has half the number of turns of the primary, the secondary voltage will be half that of the primary. So we can say that *the ratio of the secondary turns to the primary turns is equal to the ratio of the secondary voltage to the primary voltage.* In formula form it looks like this:

$$\frac{\text{Number of secondary turns}}{\text{Number of primary turns}} = \frac{\text{Secondary voltage}}{\text{Primary voltage}}$$

or simply, $$\frac{N_s}{N_p} = \frac{E_s}{E_p}$$

Let's see how these ratios may be used. For example, suppose that a supply voltage is 115 volts, and the primary winding has 1,150 turns. If we want a secondary voltage of 345 volts, how many turns must the secondary have?

$$N_s = \frac{E_s}{E_p} \times N_p$$

$$= \frac{345}{115} \times 1,150$$

$$= 3 \times 1,150$$

$$= 3450 \text{ turns}$$

This formula also may be used to find the voltage induced in the secondary when you know the number of turns and the voltage of the primary and the number of turns in the secondary. For example, how much voltage is induced in the secondary when the primary turns are 1,170, the secondary turns are 63, and the primary voltage is 117 volts?

$$E_s = \frac{N_s}{N_p} \times E_p$$

$$= \frac{63}{1,170} \times 117$$

$$= \frac{63}{10}$$

$$= 6.3 \text{ volts}$$

Of course a transformer does not generate electricity—it only transfers it from one circuit to another. In the transfer, the voltage induced in the secondary may be more or less than the voltage in the primary, depending on the turns ratio. While we may raise or lower voltages by using step-up or step-down transformers, we cannot get any more power out of the secondary than that in the primary. In fact, to be accurate, we don't get as much power from the secondary as that in the primary. Later in this lesson you'll learn why this is so. Right now, because well-designed transformers are very nearly 100-percent efficient, we will assume that we get as much power out of a transformer as we put into it. The very slight error that will result is unimportant. So we can say that the primary power equals the secondary power, or

$$P_p = P_s$$

The primary power is equal to the voltage in the primary multiplied by the current flowing in the primary, and the secondary power is equal to the voltage induced in the secondary multiplied by the current that flows in the secondary. So, if

$$P_p = E_p \times I_p$$

and

$$P_s = E_s \times I_s$$

then

$$E_p \times I_p = E_s \times I_s$$

Let's see how this works out in a practical transformer. Suppose we have a step-up transformer. The primary voltage is 117 volts, the secondary voltage is 350 volts, and the load on the secondary draws 100 ma. How much current flows in the primary (assuming the transformer to be 100-percent efficient)?

$$E_p \times I_p = E_s \times I_s$$

Substituting figures, we get:

$$117 \times I_p = 350 \times 0.1$$

$$117 \times I_p = 35$$

then

$$I_p = \frac{35}{117}$$

$$= 0.3 \text{ amp or } 300 \text{ ma}$$

Let's take another example. Suppose this time we have a step-down transformer. The primary is connected to 110 volts, and the secondary draws 2 amperes at 6.3 volts. What is the primary current?

$$E_p \times I_p = E_s \times I_s$$

$$110 \times I_p = 6.3 \times 2$$

$$110 \times I_p = 12.6$$

$$I_p = \frac{12.6}{110}$$

$$= 0.114 \text{ amp or } 114 \text{ ma}$$

From these examples, you can see that if the secondary voltage is *higher* than the primary voltage, the secondary current is *lower* than the primary current. Likewise, if the secondary voltage is *lower* than the primary voltage, the secondary current is *higher* than that flowing in the primary. We say that the current ratio is an inverse ratio to the turns or voltage ratios. Written as a formula, this becomes:

$$\frac{N_s}{N_p} = \frac{I_p}{I_s}$$

or

$$\frac{E_s}{E_p} = \frac{I_p}{I_s}$$

One very important point to remember is that the current flowing in the primary winding depends upon the current flowing in the secondary. Of course, the current flowing in the secondary depends upon the load connected to the secondary. If there is no load on the secondary (if the secondary is open), the current flowing in the primary is very small and is called the *magnetizing* current.

12-9. TRANSFORMER LOSSES

As we have said, transformers are not really 100-percent efficient; there is always some loss in power, however small it is. In designing a transformer, the manufacturer considers all the things that cause a transformer to lose power and tries to overcome them. Most transformers are better than 90-percent efficient, and first-grade transformers are better than 98-percent efficient.

Copper Losses. One form of power loss in a transformer is due to the resistance of the primary and secondary windings. Such losses are called *copper losses.* Resistance in any conductor produces heat, which, because we don't want to produce heat, must be considered a loss. Copper losses may be reduced by winding a transformer with low-resistance large-diameter wire. However, such a transformer is likely to be large and heavy. If weight and space are important in planning a piece of equipment, it may be necessary to compromise and choose wire that has a reasonable amount of resistance so that the transformer will fit where we want it to.

Flux Losses. Earlier in this lesson, you learned that some of the flux lines formed by the primary do not cut the turns of the secdary. We call this *leakage flux.* Wherever there is leakage flux, we have a power loss. You learned, too, that we can reduce leakage

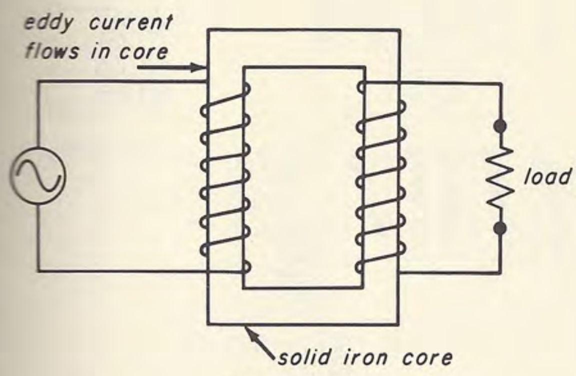
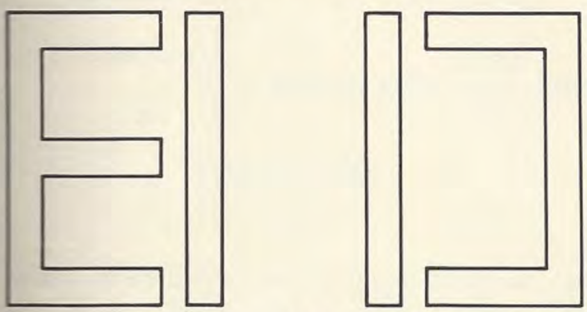


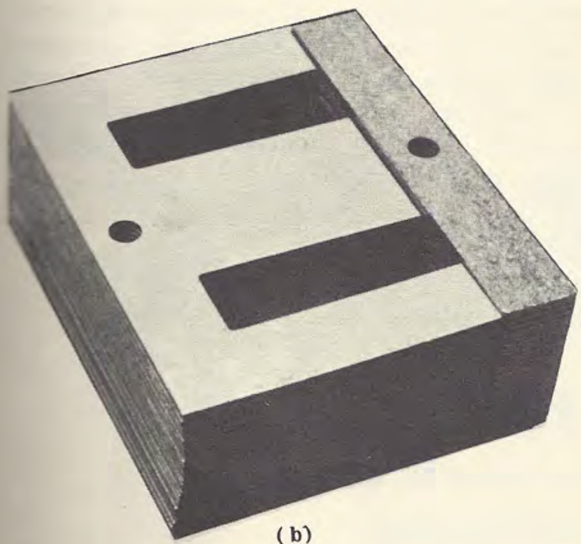
Fig. 12-29

flux by using iron cores. However the use of these cores presents us with another problem.

Eddy Currents. Any metal that moves in a magnetic field or through which a magnetic field moves has an emf induced in it. Whenever a current flows in a metal that is not part of any transformer winding, we call it an *eddy current.* When a solid iron core is used, as in Fig. 12-29, an emf is induced in the core, which causes a current to flow in the ring of the core. Such a current serves no useful purpose, so we call it an eddy-current loss. We can reduce the amount of power lost in eddy currents by using cores made from thin sheets (called *laminations*) of silicon steel. These laminations are usually 0.01 to 0.03 thick and are often shaped like those shown in Fig. 12-30*a*. The cores of most transformers are constructed of E and I laminations. Others may be constructed of C and I laminations or other shapes. A typical commercial transformer, the core of which is assembled of E and I laminations, is shown in Fig. 12-30*b*. The laminations may have an oxide coating, a coating of varnish, or some other insulation. Assembled in this way, the core provides a very poor path in which current may flow, and, as a result, there is very little eddy-current loss.



(a)



(b)

Fig. 12-30

Hysteresis Loss. Still another kind of power loss in a transformer is caused by the change in magnetic polarity that takes place in the core twice in every cycle. It is called *hysteresis* and, at times, *magnetic friction.* It causes the core to heat up and represents a loss of power. It takes energy to magnetize the core first in one direction and then in the other. The amount of energy needed to shift the molecules with each alternation in the primary current varies with the material used in forming the core. For example, a core made from silicon steel has about 1/25 the hysteresis loss of cast iron and less than 1/6 the loss of common sheet steel. You can see why silicon-steel laminations are so widely used in making transformer cores.

12-10. TRANSFORMER TYPES

Transformers of many types are used in radio and television receivers. Some of these are shown in Fig. 12-31. High frequency transformers, such as those used in radio-frequency circuits, sometimes have either air cores or powdered-iron cores. (Iron core is the name usually given to a core made from any of the magnetic materials.)

Transformers may have tapped primaries or secondaries, as shown by the schematic

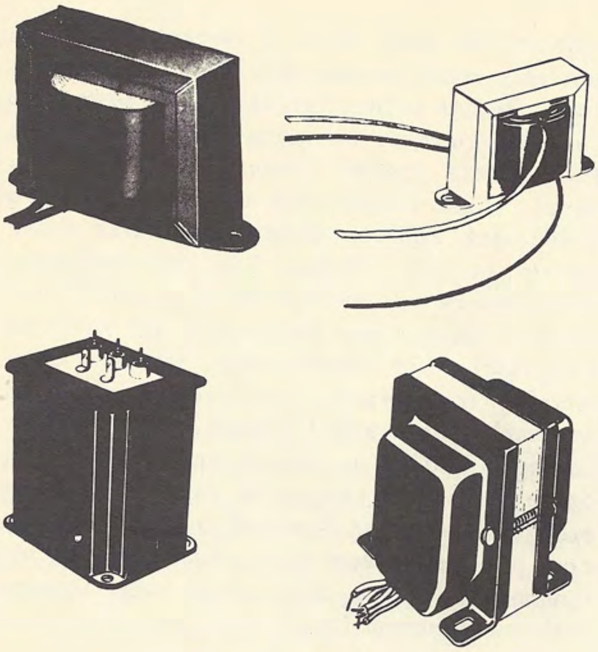


Fig. 12-31

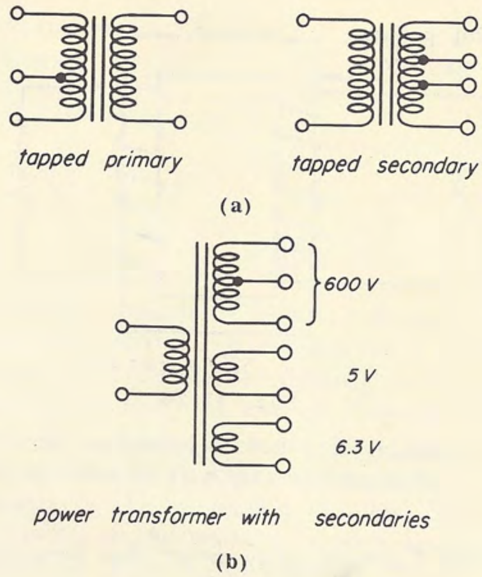


Fig. 12-32

symbols in Fig. 12-32*a*. Power transformers may have two or more secondaries, as shown in Fig. 12-32*b*. The transformer shown has one step-up secondary and two step-down secondaries. (To determine the amount of power in the primary, it is necessary to find the total power of all the secondaries, which will be slightly less than the primary power.)

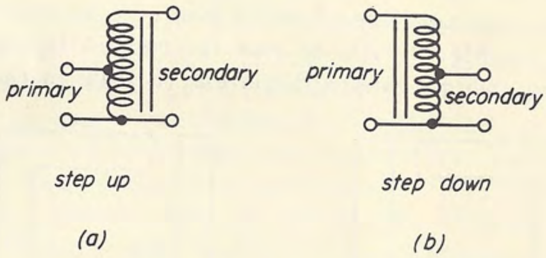


Fig. 12-33

Auto-Transformers. It is not necessary that the primary winding and the secondary be separate. In one type of transformer, called the *auto-transformer,* the primary may be part of the secondary, in a step-up transformer (shown in Fig. 12-33*a)*, or, in a step-down transformer, the secondary may be part of the primary, as shown in Fig. 12-33*b*. The turns ratio of an auto-transformer is equal to the voltage ratio (as in standard transformers) and inversely equal to the current ratio. Auto-transformers are seldom used where the voltage ratio is very high. Because the primary and secondary are not separate windings, it is sometimes dangerous to connect certain types of line-powered test equipment to receivers powered by auto-transformers. However, very few receivers are powered by such transformers.

ELECTRONIC FUNDAMENTALS

EXPERIMENT LESSON 12

METER ASSEMBLY AND A-C MEASUREMENTS

RCA INSTITUTES, INC.
A SERVICE OF RADIO CORPORATION OF AMERICA
HOME STUDY SCHOOL
350 West 4th Street, New York 14, N. Y.

Experiment Lesson 12

PART 1

OBJECT

1. To wire the a-c section of the multimeter.

2. To calibrate the a-c section of the multimeter.

EQUIPMENT NEEDED

Kit 6

Soldering iron and stand

Cloth for cleaning soldering iron

Long-nose pliers

Cutting pliers

Penknife, awl, or scriber

12¼-inch length of solid pushback wire

PREPARATION

1. Unpack the parts in Kit 6 carefully, and check them against the parts listed and pictured on page 2 of Experiment Lesson 11. Return immediately any parts that you find broken or obviously defective, together with the packing slip, to the address given on the packing slip. Put the choke aside for use in future lessons.

2. Clear your workbench or table and arrange your tools for easy use.

3. Make sure that your soldering iron is tinned and cleaned.

4. Look at Fig. 12-1 and 12-2 to see the assembling and wiring that you are going to do in this lesson.

JOB 12-1

To connect the two diode holders together.

Procedure.

Step 1. Examine the two diode holders that came to you in Kit 6. They are exactly alike. Each holder has two clips. Figure 12-3*a* shows one of the diode holders. The left-hand clip is labelled clip 1, and the right-hand clip is labelled clip 2. In the following steps, you are going to connect clip 1 of one diode holder to clip 2 of the other diode holder.

Step 2. Place the diode holders on your work table as shown in Fig. 12-3*b*. The diode holder to the left is diode holder 1 and the diode holder to the right is diode holder 2.

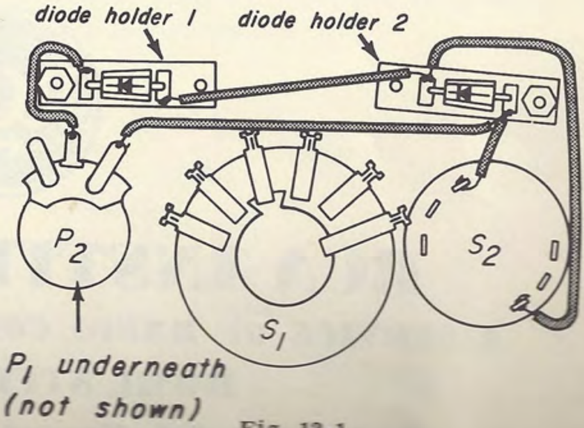


Fig. 12-1

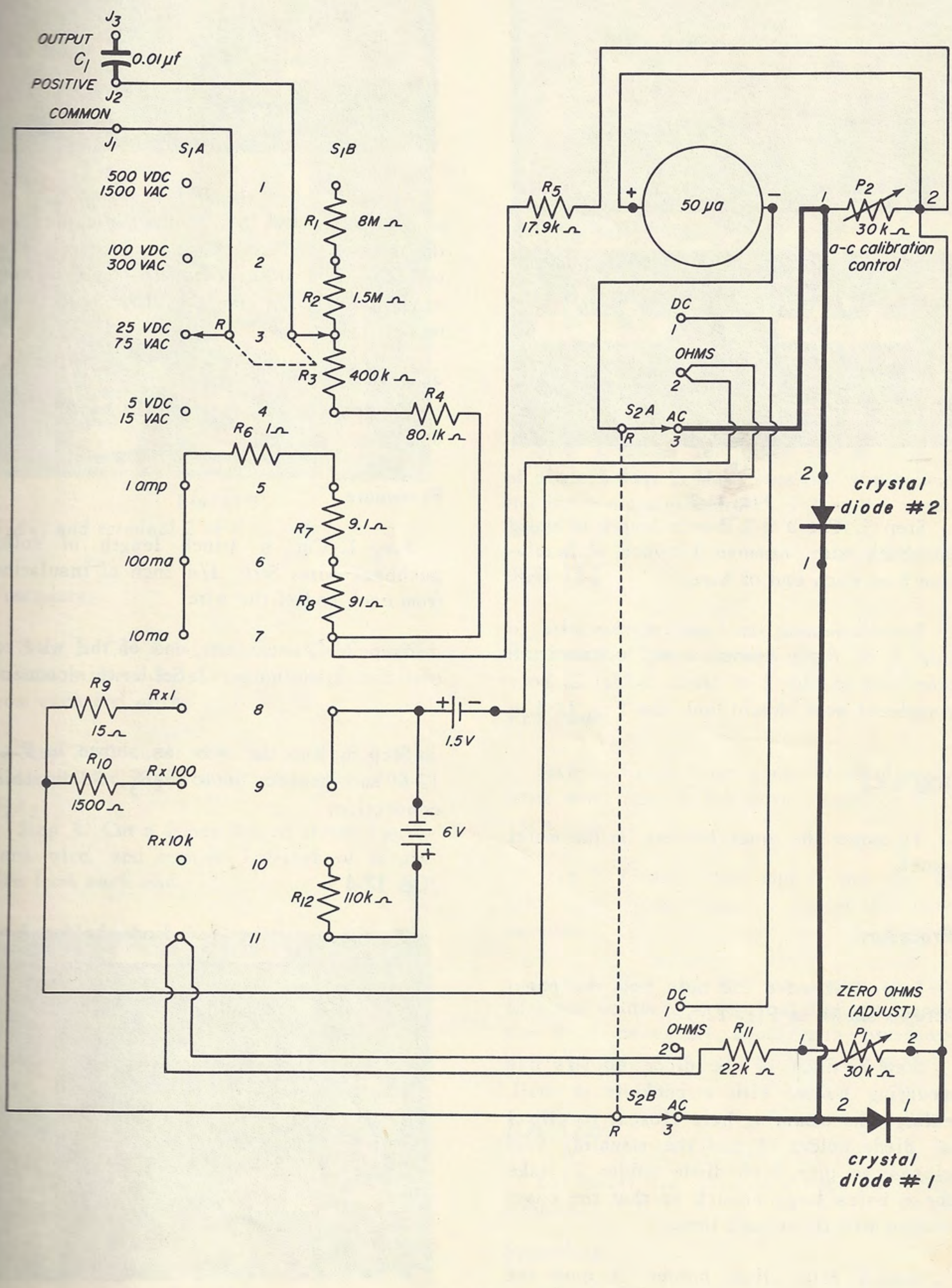
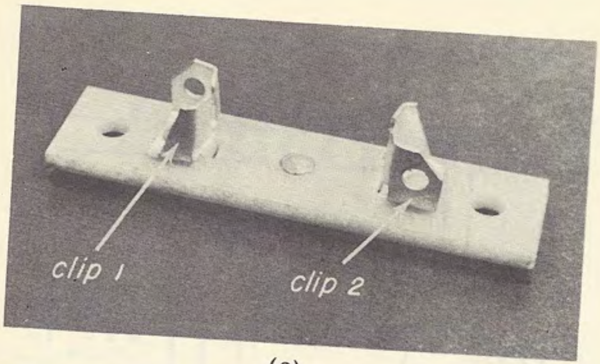
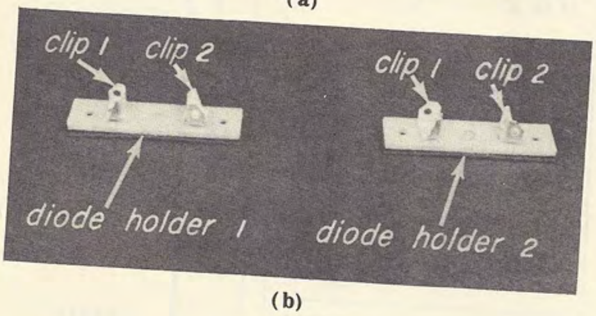

J3
OUTPUT
C1
0.01μf
POSITIVE
J2
COMMON
J1
S1A
S1B
500 VDC
1500 VAC
1
R1
8M Ω
100 VDC
300 VAC
2
R2
1.5M Ω
25 VDC
75 VAC
R
3
R3
400k Ω
5 VDC
15 VAC
4
R4
80.1k Ω
R6 1Ω
1 amp
5
R7
9.1Ω
100ma
6
R8
91Ω
10ma
7
R9
Rx1
15Ω
8
1.5V
R10
Rx 100
1500Ω
9
6V
Rx10k
10
R12
110k Ω
11
R5
17.9k Ω
50 μa
P2
30k Ω
a-c calibration
control
DC
OHMS
S2A
AC
crystal
diode #2
ZERO OHMS
(ADJUST)
R11
22k Ω
P1
30k Ω
S2B
crystal
diode # 1

Fig. 12-2



(a)



(b)

Fig. 12-3

Step 3. Cut a 2-1/2-inch length of solid pushback wire. Remove 1/4-inch of insulation from each end of wire.

Step 4. Solder one end of the wire to clip 2 of diode holder 1 and connect the other end to clip 1 of diode holder 2. Your completed work should look like Fig. 12-4.

JOB 12-2

To mount the diode holders on the meter panel.

Procedure.

Step 1. Remove the nuts from the panel screws shown in Fig. 12-5.

Step 2. Each of the diode holders has mounting holds. With a penknife or drill, enlarge the mounting hole closest to clip 1 of diode holder 1 and the mounting hole closest to clip 2 of diode holder 2. Make these holes large enough so that the panel screws will fit through them.

Step 3. Slip diode holder 1 over the panel screw just above potentiometer P_2 and slip diode holder 2 over the panel screw

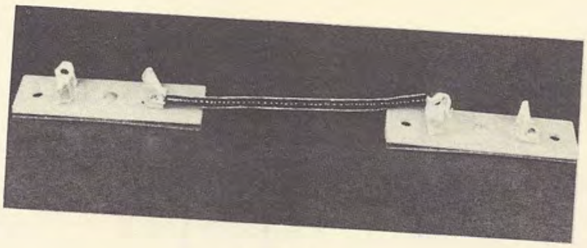


Fig. 12-4

just above switch S_2. Replace the nuts on the screws and tighten them securely but not too much. If the nuts are tightened too much, they may cause the diode holders to break.

JOB 12-3

To connect clip 1 of diode holder 2 to S_2B_3.

Procedure.

Step 1. Cut a 4-inch length of solid pushback wire. Strip 1/4 inch of insulation from each end of the wire.

Step 2. Connect one end of the wire to clip 1 of diode holder 2. Solder this connection.

Step 3. Run the wire as shown in Fig. 12-6 and connect it to S_2B_3. Solder this connection.

JOB 12-4

To connect clip 2 of diode holder 2 to

Fig. 12-5

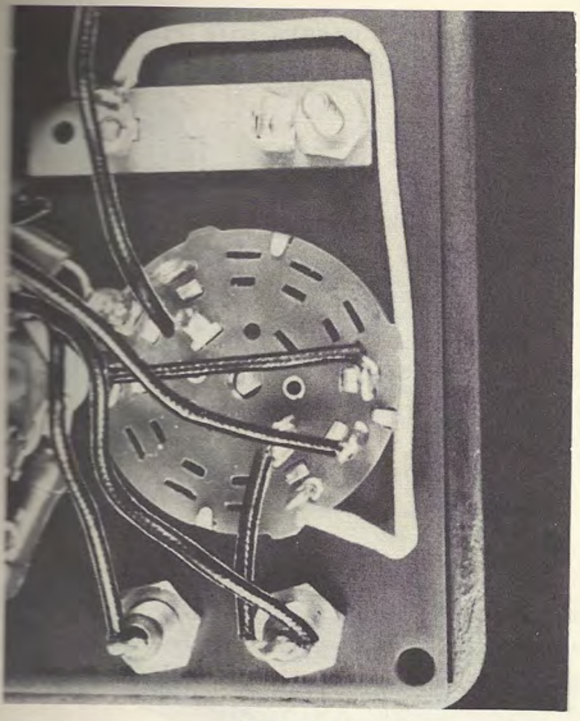


Fig. 12-6

S_2A_3, and terminal 1 of P_2.

Procedure.

Step 1. Cut a 1-1/4-inch length of solid pushback wire. Strip 1/4-inch of insulation from each end of the wire.

Step 2. Connect this wire to clip 2 of diode holder 2 and solder the other end to S_2A_3.

Step 3. Cut a 4-inch length of solid pushback wire, and remove 1/4-inch of insulation from each end.

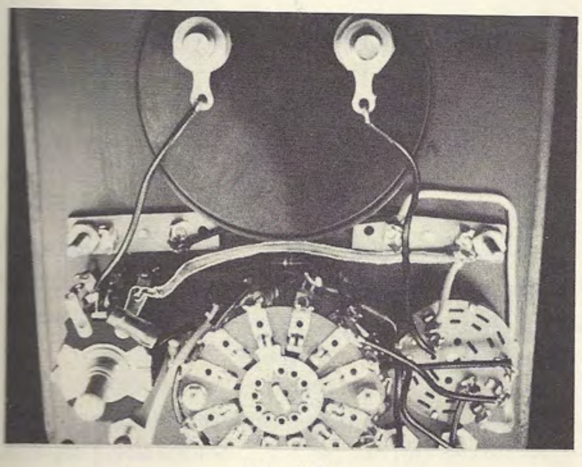


Fig. 12-7

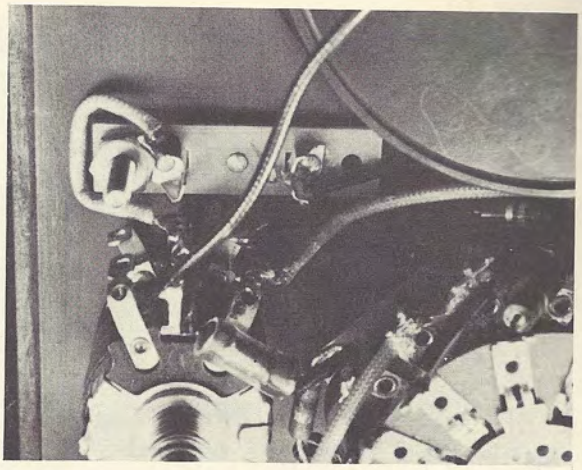


Fig. 12-8

Step 4. Run the wire as shown in Fig. 12-7, and solder one end to terminal 1 of potentiometer P_2.

Step 5. Solder the other end to clip 2 of diode holder 2. Make sure that you solder the other connection to clip 2 at the same time.

JOB 12-5

To connect clip 1 of diode holder 1 to terminal 2 of potentiometer P_2.

Procedure.

Step 1. Cut a 2-inch piece of solid push-back wire. Strip 1/4-inch of insulation from each end.

Step 2. Connect one end of the wire to clip 1 of diode holder 1. Solder this connection.

Step 3. Run the wire as shown in Fig. 12-8 and solder it to terminal 2 of potentiometer P_1. If necessary, unsolder the previously made connection before doing this step.

JOB 12-6

To insert the crystal diodes in their holders.

Procedure.

Step 1. The crystal diodes you received

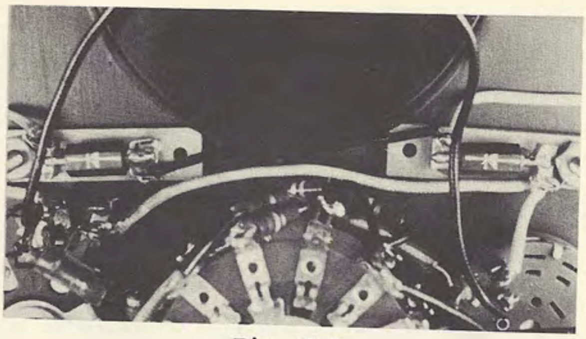


Fig. 12-9

in Kit 6 are identical. With cutting pliers, clip the pigtails off the terminals on both ends of both diodes.

Step 2. Insert the diodes in their holders so that the arrows point in the direction shown in Fig. 12-9.

JOB 12-7

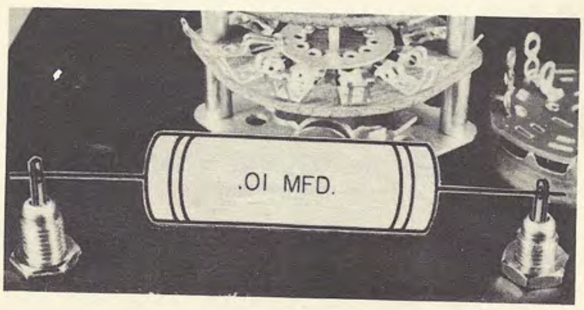
To connect capacitor C_1 between jacks J_2 and J_3.

Procedure.

Step 1. Apply the tip of your hot soldering iron to the soldered joint on jack J_2. When the solder is melted, insert the tip of an awl or scriber into the soldering lug of the jack so that you can make room for inserting one of the tinned leads of the capacitor.

Step 2. Center the capacitor between J_2 and J_3, as shown in Fig. 12-10, with one capacitor lead inserted in the lug of J_2 and the other in the lug of J_3.

Step 3. Make a good tight joint at each



lug, remove the excess wire with your cutting pliers, and solder each connection.

Discussion. You have just completed the assembly of the a-c section of your multimeter. The object of the next part of this lesson is to calibrate your meter.

JOB 12-8

To calibrate the a-c section of your multimeter.

Procedure.

Step 1. Check with your local electric company to determine *exactly* how much voltage is being supplied to the outlet plugs in your home. The voltage will probably be between 110 and 120 volts.

Step 2. Insert the black test lead into the black pin jack of your multimeter and insert the red test lead into the red pin jack.

Step 3. Turn the FUNCTION switch on your meter to AC position and the RANGE switch to the 300 VAC position.

Step 4. One at a time, insert the test prods into a convenient a-c outlet, as shown in Fig. 12-11.

Step 5. Carefully adjust potentiometer P_2 until the reading on your meter scale is exactly the same as the value of the voltage coming from your outlet (the value you learned from the electric power company).

Step 6. Remove the test leads from the a-c outlet and your meter.

Discussion. You have just calibrated the a-c section of your meter. You will not need to calibrate this part of your meter again until you replace a crystal diode or some other part of your meter.

Now that you have assembled and calibrated your meter, let us discuss the purpose of the parts in the a-c section. When you as-are sure that you understand the theory of electromagnetic induction and transformer action, do these experiments. If something comes up that puzzles you while you are performing an experiment, do not hesitate to go back to the theory lessons for the answer.

In order to perform the experiments in the first part of this lesson, it will be necessary to remove the meter from the multimeter. This is done in the following manner:

Step 1. Unscrew the four screws that hold the meter panel to the meter case.

Step 2. Remove the four meter-mounting nuts and lock washers that hold the meter to the panel. Free the two diode holders from the meter mounting screws.

Step 3. Loosen the hex nut that holds the soldering lug to the positive terminal of the meter. Do the same for the nut that holds the soldering lug to the negative terminal.

Step 4. Carefully slip the meter free from the soldering lugs and the four mounting holes in the panel, and place it carefully on your bench.

Step 5. Place the meter-mounting nuts and lock washers, together with the panel screws, in the bottom of the multimeter case where you can find them when you need them. Replace the multimeter panel on top of the case without screwing it to one side for your use later on.

Warning: While the meter is disconnected from the multimeter, do not use it for any purpose except as called for by the instructions that follow.

EQUIPMENT NEEDED

1. One 40-penny nail

2. Magnet wire

3. Two bar magnets

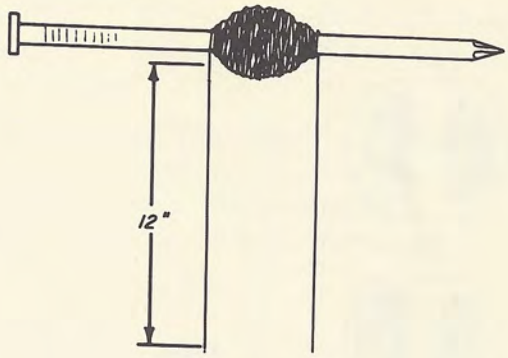


Fig. 12-12

4. Multimeter

EXPERIMENT 12-1

To induce an emf in a coil of wire by causing a magnet to be moved so that the lines of force (flux) of its field cut across the coil's windings.

Procedure.

Step 1. Wind 200 turns of magnet wire on the 40-penny nail. Try to make the turns as

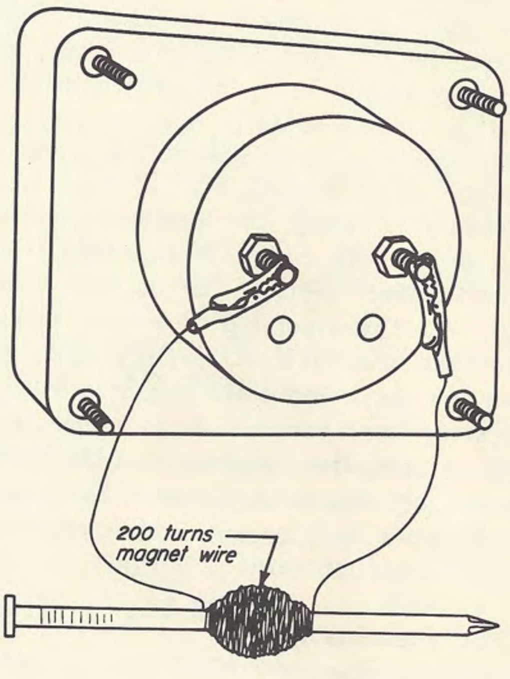


Fig. 12-13

close together as you can. Leave 12 inches of free wire at each end of the nail, as shown in Fig. 12-12.

Step 2. Unsolder the alligator clips from the 4.5-volt battery that you last used in Experiment Lesson 9. Solder one clip to each end of the coil you have just wound.

Step 3. Clip one end of your coil to the positive terminal of the meter and the other end to the negative terminal, as shown in Fig. 12-13.

Step 4. Hold a bar magnet at the end near the North pole of the magnet, as shown in Fig. 12-14*a*. Hold the North pole close to one end of the coil wound on the nail, as shown in Fig. 12-14*b*. Then slowly move the magnet to the other end of the coil, using a steady, even motion. (Do not jerk the magnet.) As you do this, watch the meter needle. Notice the direction in which the needle moves.

Step 5. Move the magnet slowly in the opposite direction so that it goes back to its first position over the coil, as shown in Fig. 12-14*c*. As you do this, notice once again the direction of the needle's movement.

Step 6. Repeat Steps 4 and 5, using the South pole of the magnet instead of the North pole. In each case, observe carefully the direction in which the meter needle moves. Compare the direction of movement with the direction you noticed in Steps 4 and 5.

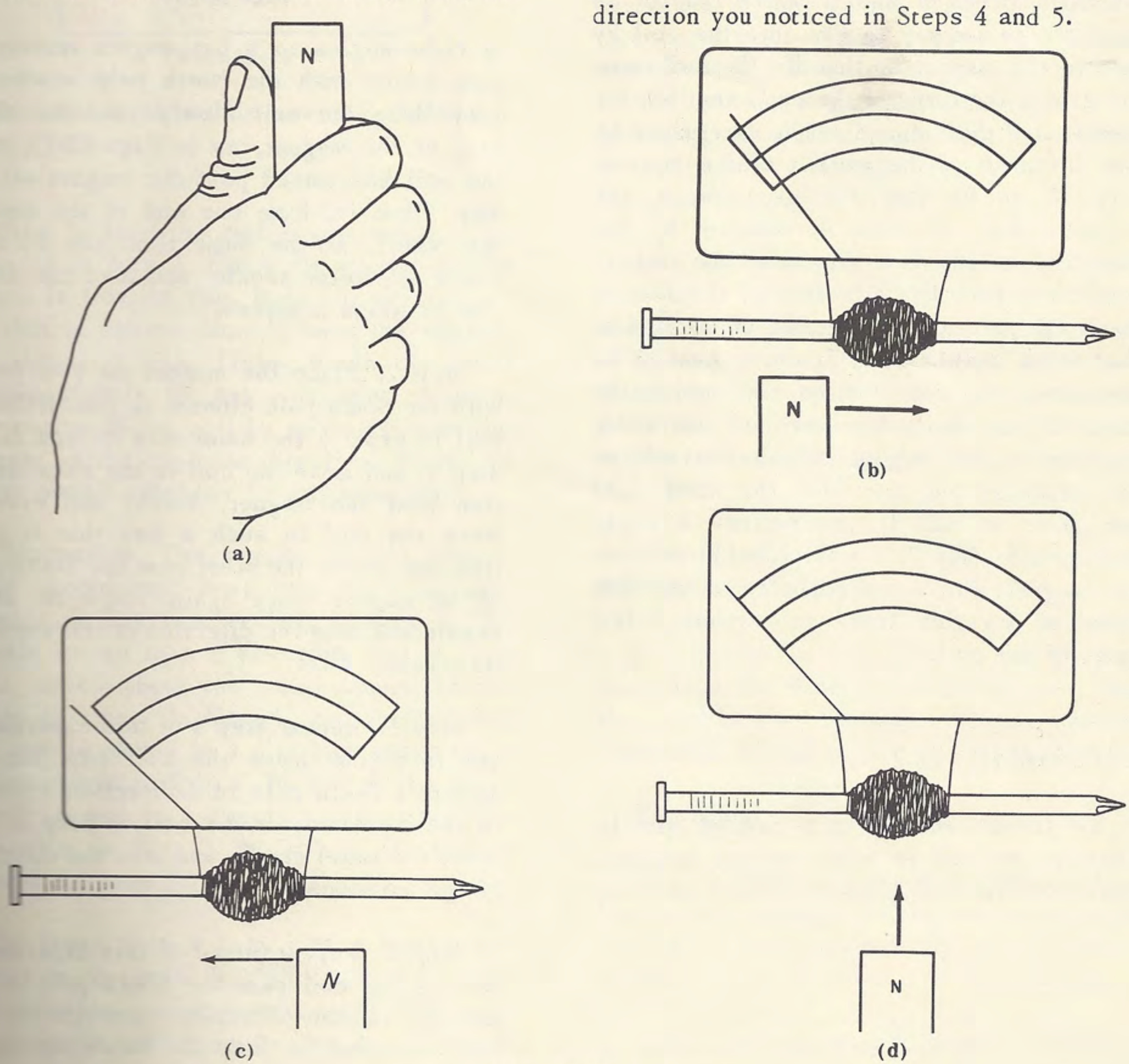


Fig. 12-14

Step 7. Place the magnet in the position shown in Fig. 12-14*d* and then slowly move it in the direction shown by the arrow. As you do this, watch the meter needle carefully for any signs of movement.

Discussion. If you followed all of the directions given in Experiment 12-1, you found that in Step 4 the meter needle moved slightly either above or below zero. In Step 5, the needle moved in a direction opposite to its movement in Steps 4 and 5. As for Step 7, there was little or no movement at all of the meter needle.

Let us see what we may learn from these findings. Steps 4 and 5 prove that it is possible to induce an emf into the coil by moving the magnet so that its lines of force cut across the turns of the coil, and that the direction of the induced emf is determined by the direction of the motion of the magnet. Step 6 shows that the direction of the induced emf is also determined by the direction of the flux (because the change was made from the direction of the flux at the North pole to the direction of the flux at the South pole). Step 7 shows that it is necessary for the flux to cut across the turns of the coil, because, in this case, you moved the magnet in the direction of the windings and saw that the needle did not move at all. If you noticed a slight movement in Step 7, it was probably because the magnet was moved in such a way that some of its flux lines cut across a few turns of the coil.

EXPERIMENT 12-2

To induce an emf in a coil of wire by causing the coil to move so that its turns cut across the flux lines of a fixed magnetic field.

Procedure.

Step 1. Use the coil that you made in Experiment 12-1. Hold the coil at one end, at right angles to a bar magnet resting on your bench with the North pole nearest to you. Move the coil slowly past the North pole of the magnet, as in Fig. 12-15, until the coil has moved past the magnet all the way, (that is, from one end of the coil to the other). At the same time you do this, watch the meter needle and note the direction in which it moves.

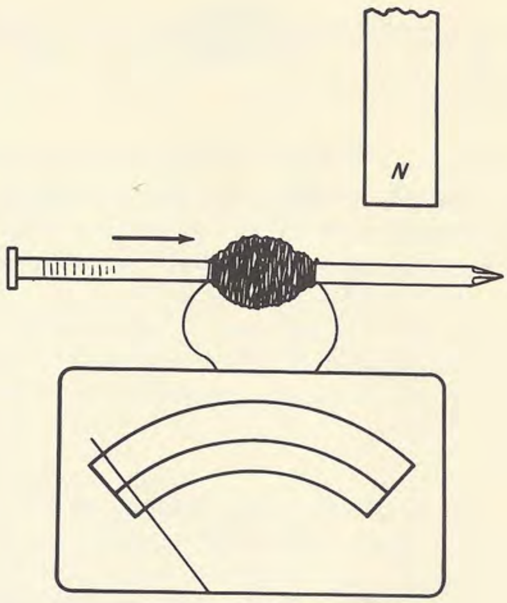


Fig. 12-15

Step 2. Place the magnet on your bench with the South pole closest to you. Hold the coil in exactly the same way as you did in Step 1, and move the coil in the same direction past the magnet, slowly and evenly. Move the coil in such a way that it goes from one end to the other past the South pole of the magnet. Once again, watch the meter needle and note the direction of the needle's movement.

Step 3. Repeat Step 1 of this experiment, but this time move the coil past the bar magnet's North pole in a direction opposite to the movement of the coil in Step 1. Observe the meter needle and note the direction of the movement.

Step 4. Repeat Step 2 of this experiment, moving the coil past the South pole of the magnet in the direction opposite to the coil's motion in Step 2. Watch the meter needle as you do this, and compare the

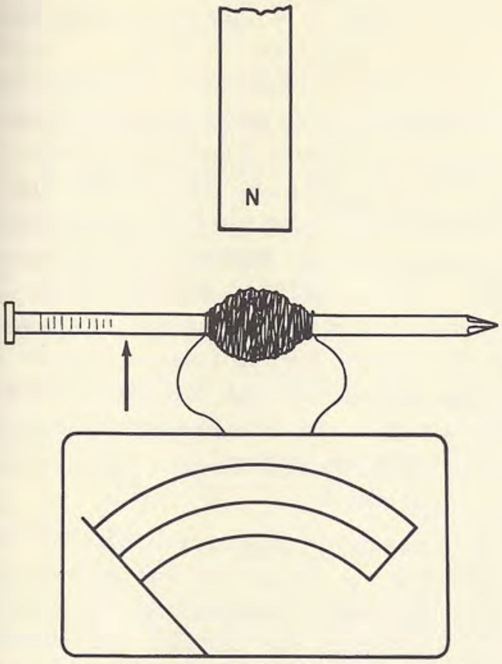


Fig. 12-16

way in which the needle moves to the way it moved in Step 2.

Step 5. Hold the coil at one end, just as you did in Step 1. Place the magnet on the bench in front of you. Move the coil slowly so that it passes directly over the magnet, as shown in Fig. 12-16. Watch the meter needle closely for any movement. Reverse the motion of the coil by moving it over the magnet in the opposite direction. Watch the meter needle carefully for any movement.

Discussion. The results of this experiment should have been very much like the results of Experiment 12-1. In Step 1, the needle moved in one direction, and in Step 2 it moved about the same amount in the other direction. In Step 3, you noticed that the needle moved in a direction opposite to its movement in Step 1. In Step 4, the meter needle moved in a direction opposite to its movement in Step 2. In Step 5, the needle should not have moved at all.

In Steps 1 to 4, why was a current induced in the coil? Why did it flow through the meter and cause a movement? Just as it is possible to induce an emf into the coil by moving a magnet in such a way that its flux lines cut across the turns of the coil, it is also possible to induce an emf into the coil by moving the coil instead of the magnet. Once again we see that the direction of the meter needle's movement depends upon the direction of the flux lines; the meter needle changed its direction when the coil moved past the South pole of the magnet instead of the North pole. The needle moved in one direction when the coil was moved from right to left.

Does it make any difference whether the magnet moves or the coil moves when you wish to induce an emf into the coil? You proved in Experiments 12-1 and 12-2 that it doesn't make any difference which one moves. Two things are necessary in order to induce an emf into a coil. First of all, there must be movement between the magnet and the coil. We refer to this as *relative motion* between a coil and a magnetic field. Secondly, the motion must be in such a way that the turns of the coil are cut by the flux lines of the magnetic field.

In Experiments 12-1 and 12-2, you were interested in the direction of the meter needle's movement, rather than in the amount of movement of the needle. Now let us see what determines the relative *amount* of emf induced. Remember that the greater the needle swing, the greater is the induced voltage.

EXPERIMENT 12-3

To induce an emf into a coil of wire using first the field of one bar magnet, then the field of two bar magnets, and compare the amount of emf produced.

Procedure.

Step 1. Repeat Step 4 of Experiment 12-1. Record the readings. (If the needle moves to the left of zero, reverse the meter connections.)

Step 2. Hold two bar magnets together, with like poles facing the same way. With

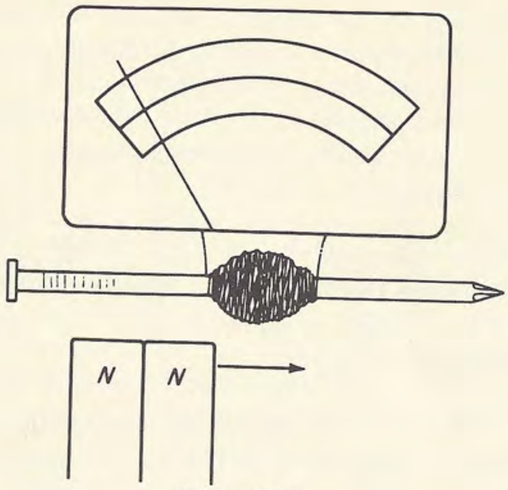


Fig. 12-17

the north poles nearest the coil, as in Fig. 12-17, slowly move both magnets from one side of the coil to the other, using a steady motion. Compare this reading with the reading you obtained in Step 1.

Step 3. Repeat Steps 1 and 2, using the south poles in each case. When you do this with the two magnets, be sure that like poles are placed side by side. Compare the amounts of emf produced in each case.

Step 4. Place one bar magnet on the bench, with the north pole near you. Repeat Step 1 of Experiment 12-2. (If the meter needle moves to the left of zero, place the opposite pole of the bar magnet in a position nearest to you.) Write down the reading.

Step 5. Hold the other bar magnet next to the first one, so that both north poles are near you. Starting at one end of the coil, as shown in Fig. 12-18, move the coil past the two magnets slowly and evenly, until the other end of the coil passes the magnets. Write down the distance that the needle moves. Compare the result with the amount of emf obtained in Step 4.

Step 6. Repeat Steps 4 and 5 with the other pole of first one magnet nearest to you, and then both magnets. Compare the amounts of emf induced in each case.

Discussion. If you followed the directions carefully, the amount of emf that was induced in Step 2 of this experiment should have been twice as much as the amount found in Step 1. Likewise, Step 5 should have shown that the reading you obtained on the meter was about double the amount you put down for Step 4. The reason for the differences in the amounts of emf induced is the increase in the strength of the magnetic field due to the addition of a bar magnet. The magnetic field of two bar magnets is twice as great as that of one bar magnet; that is, two bar magnets placed with like poles touching have about twice the number of lines of force as one bar magnet.

As a result of this experiment, you have proved that the amount of emf induced in a coil depends on the strength of the magnetic field. Therefore, the stronger the magnetic field, the greater will be the emf that is induced; the induced emf will be greater if more lines of force cut across the turns of the coil. The induced emf will be smaller if fewer lines of force cut across the turns of the coil.

EXPERIMENT 12-4

To induce an emf in a coil of wire by having the flux lines cut the turns of the

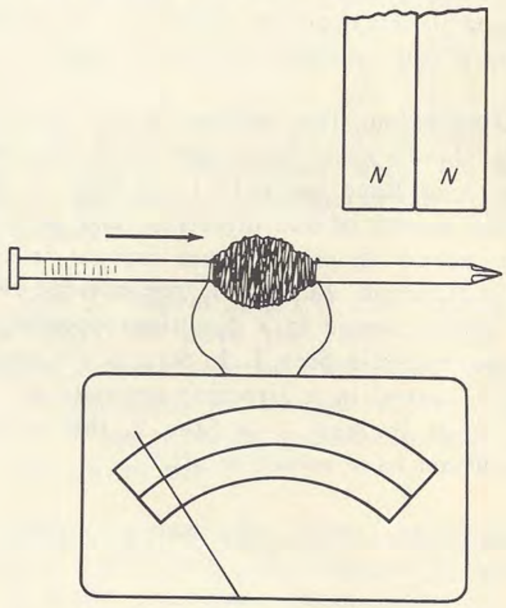


Fig. 12-18

coil slowly, then rapidly, and compare the amount of emf produced.

Procedure. In this experiment, it is very important that you try to judge the speed of movement of the magnet slowly. (Try to remember *how* slowly you actually move it.) In case the directions call for moving the magnet rapidly, be sure that you move it faster than before, and try to make a mental note of *how* fast you move it.

Step 1. Repeat Step 1 of Experiment 12-3, using the pole of the magnet that caused the meter needle to move to the right. Move the magnet *slowly*. Write down the meter reading.

Step 2. Do Step 1 of this experiment again, but this time move the magnet *rapidly*. Write down the meter reading, and compare it with the reading in Step 1.

Step 3. Repeat Step 1, using two bar magnets with like poles held together. Write down the result.

Step 4. Repeat Step 2, using two bar magnets. Write down the result, and compare it with the result obtained in Step 3.

Step 5. Now do Steps 1 to 4 over again, this time using the other pole of the magnets. Write down the amount of emf induced each time, and compare all the results.

Step 6. Repeat all the steps of this experiment, but move the coil past the magnet, as you did in Experiment 12-2.

Discussion. When you performed this experiment, you found that it was very important to follow all directions carefully, because the speed of movement of the magnet or the coil determines the amount of emf that is induced.

In Step 1, you induced a certain amount of emf in the coil, and made a note of it. Step 2 gave you a greater amount of emf, because you moved the magnet faster. If you moved the magnet twice as fast as you did in Step 1, you obtained twice as much induced emf. In case you moved it more than twice as fast, the amount of emf induced was more than double the amount that you noted first.

The other steps of this experiment produced similar results. They proved that the amount of emf induced in a coil also depends upon the *speed* at which the turns of the coil are cut by lines of force (speed of motion). The greater the speed, the greater is the amount of emf induced.

EXPERIMENT 12-5

To induce an emf in a coil of 200 turns of wire, then in a coil of 400 turns of wire, and compare the amount of emf produced.

Procedure.

Step 1. Repeat Step 1 of Experiment 12-3. Record the reading of the meter needle.

Step 2. Unsolder the alligator clip from the outer lead of the coil wound on the nail. Solder this lead to the free end of the spool of magnet wire. Wind 200 turns more on the nail (making 400 turns in all). Be sure to leave 12 inches of free wire to use as a lead.

Step 3. Solder the alligator clip to the free end of the 400-turn coil that you just made.

Step 4. Clip one end of the coil to the positive terminal of the meter movement and the other end to the negative terminal.

Step 5. Repeat Step 1 of this experiment, using the 400-turn coil. Compare the result obtained with the amount of emf induced in Step 1. (If the meter needle moves to the left of zero, reverse the meter connection.)

Step 6. In order to review the facts that you observed in the other experiments you performed in this lesson, compare the results you get with *slow* motion against *fast* motion, and with *one* magnet against *two* magnets.

Discussion. If the 400-turn coil that you made was prepared carefully, you saw that the amount of emf induced into it was about twice as great as the amount you induced into the 200-turn coil. This proves that the amount of emf induced in a coil also depends upon the number of turns of wire. The more turns of wire in the coil, the more will be the amount of the induced emf.

Now you are ready for a summary of all the things that this lesson has proven to you. First of all, an emf is induced in a coil of wire if there is a relative motion between the coil and a magnetic field, and if the lines of force cut across the turns of the coil. Secondly, the strength of the induced emf depends upon:

1. The strength of the magnetic field (the number of flux lines).

2. The speed of cutting (the speed of the relative motion between the coil and the magnetic field).

3. The number of turns of wire in the coil.

In all of these experiments, the magnetic field has been a *fixed* one. The only change you made was to use two bar magnets instead of one, but while the experiment was being performed, the number of lines of force that cut the turns of the coil remained the same.

Later you will study the effect of a *changing* magnetic field on the coil of wire, when there is a relative motion between them.